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Recycling of Fly ash-Slag based Geopolymer Cement

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Recycling of Fly ash-Slag based Geopolymer Cement

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Abstract

Fly ash/slag based Geopolymer cement is a material presenting potential of becoming a low-carbon alternative to ordinary Portland cement. With respect to sustainability the potential of recycling it after the end of its life, in OPC and GPC matrix mortars is investigated at the present thesis. The fabrication of OPC and fly ash/ slag based GPC mortars incorporating 0%, 25% and 50% fine recycled aggregate deriving for the same type of GPC binder took place. The mixes with the same replacement percentages and fine recycled aggregate deriving from OPC binder were produced to be used as comparatives. For both aggregate types, strength of the original binder, density, water absorption and alkali silica reactivity were tested. In comparison to OPC aggregates, GPC aggregates demonstrated lower density and higher water absorption, while they proved not to be prone to induce ASR expansion. The flow, density, compressive and flexural strength, water absorption and drying shrinkage of the resulting mortars were investigated. Gradual reductions in flow and density were observed with increasing replacement levels, with GPC aggregate presenting a less severe effect. The influence of GPC aggregate on water absorption, compressive and flexural strength of the OPC mortars proved to be similar to that of OPC aggregate, causing slight downgrading regardless the replacement level. Its effect on drying shrinkage was negligible in contradiction to that of OPC aggregate. In GPC mortars water absorption, compressive and flexural strength exhibited an enhancing effect with GPC aggregate replacement. On the contrary, drying shrinkage was negatively affected resulting to significantly high values. OPC aggregates replacement led to significant downgrading on most of the GPC mortar properties. Water absorption, drying shrinkage, flow and density of mortars appeared to be essentially dependent on the replacement percentage of natural by recycled fine aggregate.

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Abbreviations

ASR: Alkali Silica Reaction

FA: Fly ash

FNA: Natural Fine Aggregates

FRA*:* Fine Recycled Aggregates

FRCA: Fine Recycled Concrete Aggregates

GGBS: Ground Granulated Blast furnace Slag

GPC: Geopolymer Cement

GPC-FRCA: Fine Recycled Concrete Aggregate deriving from Geopolymer cement matrix

GPCMatrix: Mortar with Geopolymer matrix

GPC-RA: Recycled aggregates deriving form geopolymer cement matrix

NA: Natural aggregates

NAC: Concrete with Natural Aggregates

OPC: Ordinary Portland cement

OPC-FRCA: Fine Recycled Concrete Aggregate deriving from ordinary Portland cement matrix

OPCMatrix: Mortar with ordinary Portland cement matrix

OPC-RA: Recycled aggregates deriving from Ordinary Portland cement matrix

Original concrete or Mortar: the material which was crushed to produce the recycled aggregates

RA: Recycled aggregates

RAC: Recycled aggregate concrete, concrete containing recycled aggregates

RCA: Recycled concrete aggregates

w/c ratio: Water to cement ratio

WA: water absorption

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1 Introduction

1.1 Background

During the past decades, the construction industry has been under a significant pressure to reduce its environmental impact which is directly related to the most widely used construction material globally, Portland cement concrete. Specifically, concrete production accounts for approximately 7% of global carbon dioxide emissions ((Forde, 2009) sited in (Heath , et al., 2013)) while it consumes about 2-3% of global primary energy use (Juenger, et al., 2011) and 40% of the total worldwide construction aggregate production (Paine, 2009). The environmental impact of Portland cement concrete revolves around three axes: Use of raw materials, consumption of high amounts of energy and significant CO_2 emissions and big volumes of construction and demolition wastes. The need for a turn of cement industry towards sustainability has now become apparent, leading to the development of research fields investigating alternatives to limit its impact. A significantly promising field is that of recycling of construction and demolition wastes. Its aim is to provide an alternative for the non-renewable aggregate resources and a means for utilising materials that would be otherwise disposed.

Nevertheless, considering that for the manufacturing of 1ton of cement approximately 1 ton of CO_2 is produced (Davidovits, 2013), the change from the almost universal use of OPC-based concrete to one with significantly lower embodied carbon dioxide would have a marked effect on the global carbon emissions. Geopolymer cement was introduced by Davidovits in the 1970's and given its production relies on minimally processed natural materials or industrial by-products, it is estimated that its adoption in a wide scale could lead to a 40-80% reduction of carbon emissions (Davidovits, 2013). Geopolymer cement concretes have been proven not only to provide performance comparable to OPC in many applications, but also to have additional advantages, including abundant raw material resources, simple production method, rapid development of mechanical strength, no/low alkali-silica reaction (ASR) related expansion, excellent durability, high fire resistance, superior resistance to chemical attack, and the ability to immobilize toxic and hazardous wastes (Zhang, 2012; Provis & van Deventer, 2009). Additionally, the utilisation of GPC as a means for recycling construction and demolition wastes has started being investigated lately, providing encouraging results (Zhang, 2012; Shi, et al., 2015; Shi, et al., 2012).

These characteristics have made geopolymer of great research interest as an ideal material for sustainable development.

Before declaring Geopolymer cement as the ideal replacer for Portland cement it would be wise to examine all the stages from cradle to grave. According to the aforementioned three axes of the environmental impact of concrete Geopolymers do present advantages as far as raw materials, energy consumption and carbon emission are concerned. Despite that, if its use becomes widespread the management problem of construction and demolition wastes will rise up again. Therefore it is necessary to investigate whether the recycling of Geopolymer cement wastes is feasible.

1.2 Report outline

The present report comprises of seven chapters. The first chapter is the introduction to the topic of the thesis, presenting the background, motivation and the outline of the report. The second chapter presents the aims and objectives of the project. The third chapter is the literature review which comprises of three sections. The first one presents the main findings of the research on recycled aggregate concrete, the second is an overview on the chemistry and main properties of geopolymer cement, while the last one is a collation of the two previous sections, presenting the identified key points for investigation concerning the recycling of Geopolymer cement. These points formed the basis for the project plan development. The forth chapter explains the methodology and the experimental procedures that were followed. The rationale behind the project plan along with materials' composition, specimen preparation and testing are described in detail. In the fifth chapter, the obtained data are presented along with analysis and explanation of the results. The sixth chapter summarises the conclusions and presents suggestions for further research. The last chapter presents the references and bibliography.

2 Aims and objectives

The aim of the present study was to investigate whether geopolymer cement mortars and concretes would be appropriate for recycling. Through experimental procedures and theoretical investigation it was attempted to acquire a first estimation of the feasibility of producing recycled aggregates deriving from fly ash/slag based geopolymer matrices.

The main objective of the project was to evaluate the effect of Geopolymer cement recycled aggregates on the major mechanical and physical properties of Portland and fly ash/slag Geopolymer cement mortars, compared to that of Portland cement recycled aggregates The evaluation was twofold, investigating the effect of aggregate type on the mortars' properties and the significance of the recycled aggregate percentage in the mixes. Secondly, investigation of the major properties of Geopolymer cement aggregates took place in order to detect striking differences compared to those deriving from Portland cement or potential barriers for their use. Finally, the identification of points of interest, requiring further investigation in the future was within the objectives of the research.

The experimental plan was developed based on the testing followed for recycled aggregate concretes, taking under consideration the main findings of the literature on Geopolymer cement properties.

3 Literature review

3.1 Recycled Aggregates& Recycled Aggregate Concrete

3.1.1 Introduction

Recycled concrete aggregates (RCA) present distinct physical and chemical characteristics compared to natural Aggregates (NA), which affect significantly the properties of fresh and hardened concrete. The major difference between NA and RCA is the adhered mortar at the surface of the latter. Specifically fine recycled concrete aggregates (FRCA) are essentially composed of mortar and hardened cement paste, because the consecutive stages of crushing make the coarse fraction of RCA lose part of the adhered mortar, which accumulates in the finer fraction (Silva, et al., 2014b; Zhao, et al., 2015; Wai , et al., 2012).

In the following section the most distinct properties of RCA and their effect on Recycled aggregate concrete (RAC) mixes are overviewed.

3.1.2 Recycled aggregate properties

3.1.2.1 Density

The bulk density of RCA is compared to that of light weight aggregates (Dhir, et al., 1999). The lower density of RCA and thus higher porosity is attributed to the hardened mortar adhered to their surface (Wai , et al., 2012; Dhir, et al., 1999). Since mortar is less dense than NA, the more the adhered cement paste in RCA, the lower the density of the aggregate. Density is also affected by the strength of the original mortar, since high strength mixes require lower w/c ratios resulting in less porous structures (Silva, et al., 2014b). Finally it is depended on size of aggregate. The fine fraction density decreases with increasing processing level while the density of the coarse fraction increases. This is because the level of process determines the amount of mortar remaining adhered on the aggregate which increases as the fraction size decreases (Silva, et al., 2014b; Wai , et al., 2012). However, for the same cement and original aggregate the density of recycled concrete aggregates does not vary much even for widely different water-cement ratios of original concrete. (Hansen, n.d.)

Density of RCA has been directly related the cube strength, elastic modulus and water absorption of the resulting mixes in numerous studies.

3.1.2.2 Water absorption

The most striking characteristic of RCA is their significantly higher water absorption (WA) compared to natural aggregates. Specifically, WA values ranging from 3.6% to 8% for coarse RCA and 8% to 12% for FRCA are reported in several studies with the corresponding NA value being 0.5-1% (Hansen, n.d.; Akash Rao, 2007). RCA WA seems to be affected by the size of the particle fraction for given type and quality of original concrete. Despite some fluctuations most of the values are within the same range for a particular aggregate size. This characteristic is connected with the mortar adhering to the original aggregate. Since hardened mortar exhibits higher porosity than that of unbound NA, as the adhered mortar content increases, so does the RCA's water absorption (Silva, et al., 2014b). This explains the higher WA compared to NA and the increasing trend observed as the fraction size decreases.

The WA of RCA influences directly the workability of the resulting mixes, as the adhered mortar has the ability to absorb the available water during mixing, resulting to less free water in the mix. In fact the high WA of RCA and their initial moisture conditions can lead to modification of the nominal w/c ratio and the resulting compressive strength of the mix (Pepe, et al., 2014). Additionally, aggregate porosity and water absorption affect the water

absorption of the resulting mortar. Finally, some studies have related RCA WA with the mortar permeability and consequently with its resistance to chloride ingress (Paine & Dhir, 2010).

3.1.2.3 Presence of deleterious substances

RCA could be produced from recycled precast elements and cubes after testing or demolished concrete buildings. Whereas in the former case the aggregate could be relatively clean, in the latter it could be "contaminated". It has been suggested that RCA may have higher sulphate content than NA because of sulphates from cement in the adhered mortar (Silva, et al., 2014b; Paine , 2010). Also, the use of RCA poses the danger of non-water-soluble chlorides bound with the solid paste to become available in the long term. Therefore it is recommended that chloride contributions from RCA should better be determined from an acid-soluble test (Paine , 2010; Paine & Dhir, 2010). Finally, it is important that the alkali content of the constituents should be limited to avoid the expansive Alkali-Silica reaction (ASR). The presence of alkalis, usually from cement, and reactive silica in aggregates may lead to ASR. Concerns are often raised over the use of RCA because they can contain fractions of alkali-rich hydrated cement in the crushed concrete fractions. (Paine , 2010). Therefore, it is appropriate to generally regard RCA as a potentially reactive aggregate unless it has been established as innocuous. In both cases, the possibility of unpredictable composition variability should be considered (Silva, et al., 2014b).

The existence of these chemical substances could trigger deleterious reactions in the mortar leading to expansion and deterioration of the matrix.

3.1.3 Recycled aggregate concrete properties

The main literature findings concerning the effect of RCA on the properties of the resulting concrete mixes and the correlation between the aggregate and mix characteristics are presented in the following section.

3.1.3.1 Density

Natural air contents of fresh Recycled Aggregate Concrete (RAC) have been found to be higher and more variable than natural air contents of fresh control mixes made with NA

(Hansen, n.d.). Densities of fresh RAC have been reported to be between 85% and 95% that of control mixes. In studies concerning the effect of FRCA it was found that by replacing the natural sand with recycled sand, the fresh density of mortar decreases (Zhao, et al., 2015; Khatib, 2005). There is a consensus that mixes incorporating either coarse or fine RCA present lower density compared to control mixes with NA. It was observed that in most cases the property followed a downward trend with increasing replacement percentage. The decrease can be correlated with the lower density of the RCA attributed to the presence of the adhered cement paste.

3.1.3.2 Workability

Generally, in NAC mixes little water is required to compensate for the water absorbed by the aggregates during mixing, while in RAC mixes aggregates present higher WA, soaking the free water which lends workability to the mix (Silva, et al., 2014a) . It is reported that the effect is much more detrimental for high replacement levels of RAC such as 50% (Evangelista & de Brito, 2007; Akash Rao, 2007). Two different approaches have been suggested in order to overcome that issue, the first suggesting pre-soaking of aggregates, and the second, formulated by Leite in 2001, the addition of extra mixing water (Leite, 2001). FRCA have been proved hard to recycle in concrete as they induce a larger water demand leading to extremely dry mixes (Zhao, et al., 2015). Given they are generally coarser and more angular than desirable for production of good concrete mixes, a definite trend of a gradual reduction in workability with increase in RCA content (coarse, fine or both) was identified. It is suggested to limit the replacement level below 30% and 20% for coarse and fine RCA correspondingly to avoid significant effects on fresh properties and stability of concrete mixes (Dhir, et al., 1999; Paine & Dhir, 2010).

3.1.3.3 Compressive Strength

The compressive strength of concretes and mortars incorporating coarse RCA has been found in most cases 10%-24% lower than that of the NAC control mixes, with the decrease depending on the replacement percentage (Hansen, n.d.). It is reported that the compressive strength of concrete made with both coarse and fine RCA was at about 85% that of conventional concrete, while for replacement of coarse aggregates only the corresponding value was 95% (Gerardu & Hendricks, 1985). Concretes made with 25% and 100% FRCA replacement and coarse NA presented 15% and 30% reduction in strength correspondingly.

In the study of Zhao in 2015 the compressive strength of mortars, in which some sand fractions had been replaced by the corresponding FRCA, was lower than that of the control mortar for two different w/c ratios (Zhao, et al., 2015). Moreover, the results indicated that finer fractions of FRCA have a worse influence which is partly due to their higher cement paste content, higher water absorption and lower mechanical properties. The latter is also confirmed in the research results presented by Hansen (Hansen, n.d.). It should be mentioned that a development on strength was observed after 28 days and that regardless of the RCA content, the mixes exhibit a parallel strength development with the control NAC mixes (Evangelista & de Brito, 2007; Khatib, 2005). The research of Wai in 2012 proved that the compressive strength of mortar and the FRCA replacement have an inverse quasi linear relationship (Wai , et al., 2012). The increase in concrete porosity and the presence of weak interfacial bonding between aggregate and binder matrix are mainly attributed to this situation. The explanation for this could be the existence of hydrated and non-hydrated cement in the aggregates. During setting and hardening, the new cement paste will first react with the old cement paste attached to the RCA, in which it will use some of the required water. This is the main reason that affects and reduces the formation of C_3S_2, ettringite, CH and C_6S_3H, leading to poorer strength of RAC (Tam, et al., 2009)

However, as it is confirmed by several researches that at low levels of replacement (below than 20% for fine and 30% for coarse) the effect RCA is negligible and their use does not jeopardize the mechanical properties of mortar (Evangelista & de Brito, 2007; Goncalves & de Brito, 2010; Paine & Dhir, 2010). A good example is a specific study which proved that with percentage of coarse RCA up to 30% and appropriate mix design the production of high strength concrete (50 MPa) is possible (Limbachiya, et al., 2000)

3.1.3.4 Tensile strength

Generally, no significant differences in tensile strength with the use of FRCA have been reported, although the property shows a clear decrease with increasing replacement levels (Evangelista & de Brito, 2007; Zega & di Maio , 2011; Silva, et al., 2015a).

The tensile strength of concrete does not depend on the cement content of the mix; therefore it is not particularly favoured by the additional cement incorporated in the RCA while their more porous structure probably results to a decrease.

3.1.3.5 Modulus of Elasticity

A reduction ranging from 10% to 30% is reported in numerous studies, while a downward trend of the modulus of elasticity was observed with increasing coarse RCA percentage (Hansen, n.d.; Corinaldesi, 2010; Dhir, et al., 1999). With the use of both coarse and fine RCA reductions at the range of 25%-40% have been reported when the corresponding value for coarse RCA replacement only was at about 10-30% (Hansen, n.d.).

Due to the large amount of mortar with comparatively low modulus of elasticity attached to original aggregate particles in RCA, the modulus of elasticity of the RAC mix is usually lower than that of the corresponding NAC (Paine & Dhir, 2010). For small aggregate replacement (below 30%), the mortar stiffness which is affected by the replacement does not have a great impact on the overall stiffness (Evangelista & de Brito, 2007).

3.1.3.6 Drying shrinkage

Researches investigating various combinations of strength and quality of original and resulting concrete resulted in mixes exhibiting average drying shrinkage 50% higher than the corresponding control mixes (Hansen, n.d.). In the study of Silva in 2015, when full replacement of coarse aggregates took place the RAC exhibited shrinkage 80% greater than that of the NAC mix (Silva, et al., 2015a). The effect of FRCA on drying shrinkage is much more intense as the average increase has been reported to be about 70%.

Generally, it is confirmed by many results that the drying shrinkage follows a linear increase with increasing replacement levels (Corinaldesi, 2010; Silva, et al., 2015b; Khatib, 2005). These results are not surprising as RAC contain 50% or more mortar than the corresponding control mixes and drying shrinkage increases with the contents of cement paste or mortar in the concrete. Concretes made with 30% coarse or 20% fine RCA though, did not present significant increases in shrinkage (Zega & di Maio , 2011)

3.1.3.7 Water Absorption

Research results have shown that WA either by immersion or through capillary increases analogically with the replacement percentage of RCA (Zega & di Maio , 2011). Results obtained from concretes with w/c ratios between 0.5 and 0.7 showed that water permeability of RAC was 2-5 times that of conventional OPC (Hansen, n.d.). In the test conducted by Evangelista and de Brito in 2010, FRCA replacement level of 30% led to

16.8% increase of WA, while a full replacement resulted in a 46% increase (Evangelista & de Brito, 2010).

It is confirmed by several sources that WA of RAC increases linearly with the replacement ratio and the WA of RCA (Paine & Dhir, 2010; Evangelista & de Brito, 2010). This is to be expected since RCA has a more porous structure, which extends to the matrix leading to an overall increase in the open pores in the concrete. Also, after evaluation of numerous tests it has been found that the correlation between the strength of the original concrete and that of the RAC influences the water permeability of the latter. No significant differences were observed when the strength of the original mortar was higher than that of the resulting mix, while in the opposite case the WA of the new mix was up to 3 times that of the corresponding NAC (Hansen, n.d.).

3.1.3.8 Alkali Silica Reaction

Research is generally focused on limiting the alkali content of the constituents of RAC in order to minimize the risk of expansive ASR. The results of a research on ASR induced by the adhered mortar on RCA indicated that the manufacturing procedure for concrete production and the high water absorption capacity of RCA led to cement accumulation in the Interfacial Transition Zone (ITZ). The concentration of alkalis on the surface of RCA-ITZ and the presence of reactive sand in the mortar adhering to the RCA induced ASR in 6-month concrete. The tests were conducted using RCA with siliceous potentially reactive original aggregate and high alkali cement for the new mix. (Etxeberria & Vázquez, 2010). In a similar study, it is stated that the use of RCA in concrete compounds the problem of testing for potential ASR reactivity due to the uniqueness of a given RCA. For instance an RCA obtained from a mortar with reactive aggregate and low available alkali cement could become very reactive when used in a new mix with high percentage of available alkali. On the other hand if available alkali has been converted to alkali silica gel, the reaction in RAC would not be problematic providing the available alkali was restricted in the new mix. It is also stated that testing of ASR with the existing procedures would be expected to show RCA very problematic whereas in reality it may not be, depending on the properties of the cement utilised (Gress , et al., 2000).

It is generally concluded that it is difficult to predict and estimate the alkali silica reactivity of RCA but special care should be taken to limit silica or alkalis present either through

siliceous sand in the original concrete's composition or highly alkaline cement adhered on the RCA surface, prone to induce ASR in the new mix.

3.2 Chemistry & properties of geopolymer cement

3.2.1 Introduction

Considering the main findings on the research on recycled aggregates and their effect on the properties of concrete and mortar mixes an overview on the chemistry and properties of GPCs is presented in the following section. The properties considered of special importance for GPC behaviour as RCA are investigated.

Geopolymers is a term introduced by Davidovits, but these materials could also be called man-made rocks since they are inorganic polymeric materials with chemical composition similar to that of zeolites but possessing an amorphous structure (Mandal, et al., 2014).

3.2.2 Manufacturing

Geopolymer cement (GPC) is a binding system that hardens in room temperature like ordinary Portland cement (OPC) and is manufactured by the interaction of solid aluminosilicate with highly concentrated aqueous alkali hydroxide or alkali silicate solution. Room-temperature hardening relies on the addition of calcium cations, essentially through iron blast furnace slag (Motorwala, et al., 2013; Davidovits, 2013). The production of GPC relies on minimally processed natural materials, such as calcined kaolinitic and lateritic clays, volcanic rocks and mine tailings, or industrial by-products, such as ground granulated blast furnace slag (GGBS) or fly ash. Depending on the raw materials used, GPC is categorised as: slag-based, rock-based, fly ash-based (alkali activated & slag/fly ash) and ferro-sialate-based (Davidovits, 2013).

3.2.3 Chemistry of Geopolymers

The most defining characteristic of GPC concretes is the binding phase which comprises of an alkali aluminosilicate gel with tetrahedral framework structure (Provis & van Deventer, 2009). The geopolymer is characterized as aluminosilicates containing AlO_4^- and SiO_4, as tetrahedral subunits. These subunits are of three types and the terminology poly (sialate), poly (sialate-siloxo), and poly (sialate-disiloxo) was established by Davidovits to describe them depending on the Si: Al ratio (Image 1). The subunits alternate between Si and Al

units and covalently share an oxygen atom in order to make the larger macromolecules called geopolymers. The presence of an alkali metal as a positive ion is necessary to the geopolymer structure because it balances the negatively charged aluminate. The molecular structure of geopolymers usually takes the form of a chain or a ring and can range from amorphous to semi crystalline (Mandal, et al., 2014; Davidovits, 2002; Pacheco-Torgal, et al., 2008).

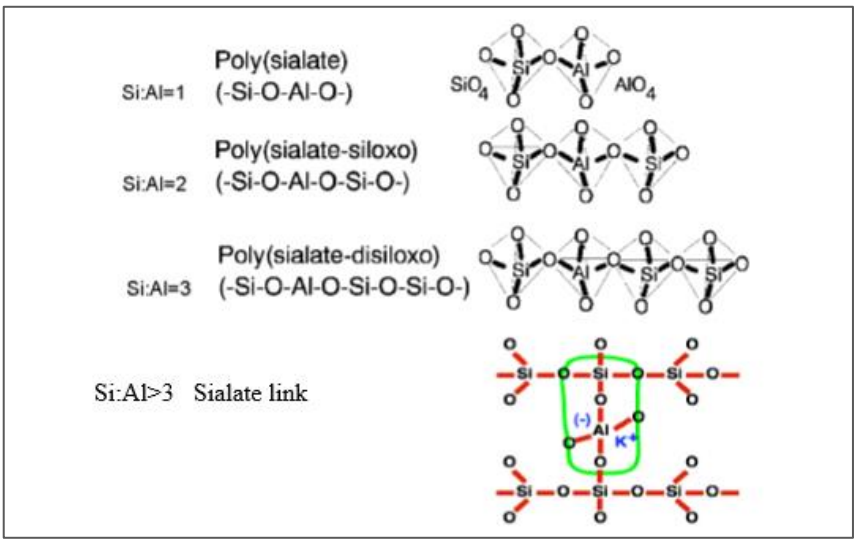


Image 1 Geopolymer cements intrinsic structure *Image source* (Davidovits, 2002)

The major occurring processes are dissolution of the aluminosilicate species within a highly basic, alkaline environment, polymerization of the dissolved minerals into short-lived structural gel, precipitation of formed hydration products similar to natural zeolites and final hardening of the matrix by excess water exclusion and the growth of crystalline structures. These stages are presented in Image 2 linearly but in reality they are largely coupled and occur concurrently. The most striking characteristic of GPC hardening mechanism is that the water plays the role of a reaction medium and then evaporates through the pores of the matrix (Duxson, et al., 2007; Rangan, 2009; Davidovits, 2013; Mandal, et al., 2014). Within these process intervals, thermodynamic and kinetic parameters become vital to gel formation and reaction degree. Several factors directly influence the degree of reaction in a mixed geopolymer paste and either enhance or detract from the polymerization process and subsequent phases which strictly define the formed cementitious properties of the hardened cement.

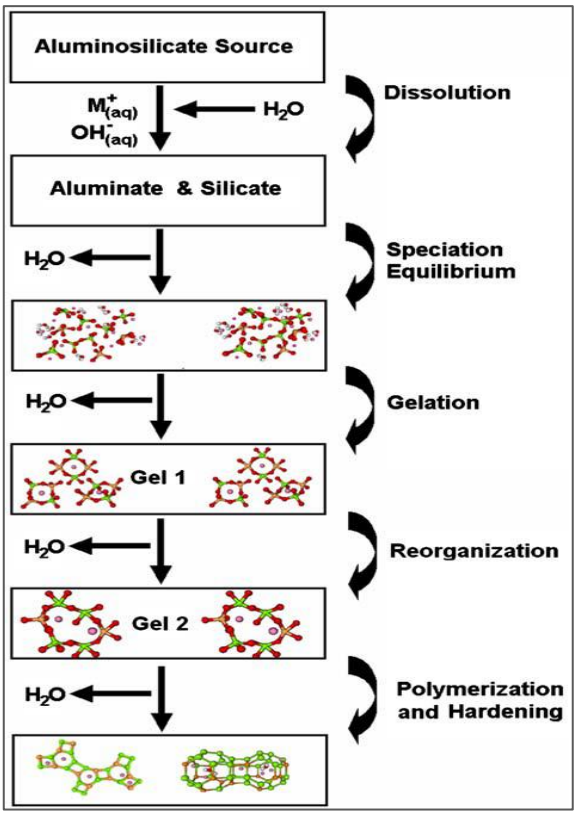


Image 2 Conceptual model for geopolymerisation *Image source* (Duxson, et al., 2007)

3.2.4 Properties of Geopolymer cement

The GPC properties are influenced by the proportions and properties of the constituent materials of the paste. Despite similarities in macroscopic characteristics of GPC prepared from different aluminosilicate sources, their microstructure, physical and chemical properties vary to a big extend. Fly ash /slag based GPC has been proved to be more strong and durable (Duxson, et al., 2007) while presenting economic advantages (Wallah & Rangan, 2006). These two factors make it ideal for high volume applications like construction; therefore the following sections will partially focus on that type of GPC.

3.2.4.1 Density

The density of GPC concrete primarily depends on the unit mass of aggregates used in the mixture (Motorwala, et al., 2013; Rangan , 2010). Tests show that the unit-weight of the low-calcium fly ash-based geopolymer concrete is similar to that of OPC concrete. In a specific test where granite-type coarse aggregates were used, the unit-weight varied between 2330 and 2430 kg/m3 (Rangan, 2009).

3.2.4.2 Compressive strength

Experimental results have shown that the interaction of various parameters on the compressive strength and the workability of geopolymer concrete is complex. With increase in concentration of sodium hydroxide solution and in the ratio of sodium silicate solution-to-sodium hydroxide solution the strength increases, while for higher molar ratio of H_2O-to-Na_2O it decreases (Rangan , 2010). Generally, GPC concretes have presented satisfactory compressive strength. They can harden rapidly in room temperature, developing strength of the range of 20 MPa within 4 hours. Depending on their composition the values vary, but it has been proved that the production of high strength concretes reaching a ceiling strength of 70-100 MPA at 28 days is possible (Davidovits, 2002). Studies have shown that GPC concretes and especially ambient cured fly ash/slag based present higher compressive strength values than OPC concretes of the same grade at 7 and 28 days (Malathy, n.d.; Rangan, 2009; Chi & Huang, 2013). The behaviour and failure mode of fly ash-based GPC in compression is similar to that of OPC with peak stress ranging from 0.0024 to 0.0026. It was also concluded that mixes with a fly ash/slag ratio of 50/50 and activated by solution with Na_2O concentrations of 6% may be the optimum mix design for fly ash/slag GPC mortars (Chi & Huang, 2013) while curing when done by wrapping with plastic bag gives better compressive strength as it preserves the moisture. (Motorwala, et al., 2013). Test results showed that most of the 28-day strength was gained during the first 2 days of curing (Wallah & Rangan, 2006)

3.2.4.3 Water absorption

It has been observed that the WA of alkali activated fly ash based GPC mortars is lower than that of OPC mortars. With Na_2O content of 4% in the activator the WA varied from 1.3% to 3.2%, whereas the value for OPC mortars was 7.5% (Chi & Huang, 2013).

3.2.4.4 Drying shrinkage

Water is released during the chemical reaction of hardening of geopolymer and for further drying periods. In specimens cured in ambient conditions this water may evaporate over a period of time causing significantly large drying shrinkage strains in the first two weeks (Rangan, 2009). Therefore, the drying shrinkage of GPC concrete cured in ambient conditions is larger than that experienced by heat-cured but in some cases it is still smaller than that of OPC mixes. In a specific study fly ash based GPC mortars of various mix

designs exhibited higher drying shrinkage than the control OPC mixes (Chi & Huang, 2013). On the other hand heat cured fly ash-based GPCs have shown very little drying shrinkage ranging in the order of about 100 microstrains after one year, which is significantly lower than the 500 to 800 microstrains experienced by OPC concretes (Rangan , 2010)

3.2.4.5 Durability

In this material the presence of $Ca(OH)_2$ is usually not detected. Given that most durability problems faced in OPC are associated with the calcium content, the degradation process of GPC is much different (Fernandez-Jimenez & Palomo, 2009). Numerous references found in literature show that alkali activated metakaolin or fly ash GPCs display very good resistance to sulphate, sea water and acid attack. Alkali activated fly ash mortars have high alkali content but very low calcium content, therefore with non-expansive aggregates ASR gel is unlikely to form. GPC concretes with alkali contents as high as 9.2% have not been reported to generate any deleterious ASR (Davidovits, 1994). Any potential ASR is more likely to happen during the original dissolution and condensation polymerisation process, while the material is still in gel form, but later reactivity is unlikely to happen since a dense zone form around each aggregate particle during curing.

3.3 Summary of literature

3.3.1 Main findings

- The adhered cement paste and hardened old mortar affect severely the properties of RCA such as density, water absorption, mechanical properties and content of deleterious substances. Specifically FRCA properties are almost completely dominated by the adhered mortar.
- Most of the RAC properties present a worsening trend with increasing replacement percentage, with water absorption and drying shrinkage being more prominently affected. Compressive strength of RAC mixes depends on a plethora of interrelated parameters.
- For replacement level of coarse RCA up to about 30% and fine RCA up to about 20% the effect on the fresh and hardened concrete properties is not significantly detrimental.

- The influence of FRCA on the mixes is much more severe compared to that of coarse RCA.
- The main differences between OPC and GPC derive from the hardening mechanisms and the binding phase. Completely different factors influence their properties.
- Ambient cured fly ash/slag based GPC demonstrates performance similar or better to OPC depending on mix design and curing conditions. The optimum proportion for fly ash/slag GPC is 50/50 and activating solution with relatively high concentration, while curing by wrapping in plastic bags results in higher strengths.
- Density, workability and strength depend mostly on the raw materials, mix design and curing method. These factors influence the hardening chemical reaction.
- GPC has lower WA in most cases depending on the alkalinity of the mix.
- Ambient cured GPC concretes exhibit higher drying shrinkage than OPC.

3.3.2 Commentary on the main literature review findings

By combining the main findings of the literature about recycled aggregate concrete and GPC concretes the following conclusions can be withdrawn.

- Most of the RCA properties depend on the adhered hardened cement or mortar. Given the striking differences of the GPC and OPC binding structures, it is expected that RCA deriving from GPC would react in a completely different way within the mortar matrices on chemical and microstructural level.
- Mechanical properties of GPC can be equivalent to those of OPC, so the properties of the RAC influenced by those factors are expected to be similar.
- WA of GPC proved to be lower than that of OPC. Also the hardening reaction of GPC concretes does not involve water absorbing. Therefore a less detrimental effect in workability and WA of the resulting mixes should be expected.
- Ambient cured GPC concretes exhibit high drying shrinkage. Although the shrinking stops after all the water has expelled from the matrix, this is a parameter that cannot be disregarded for their utilisation as RCA.
- GPC concretes have high alkalinity due to the activating solutions and the existence of undetected unreacted pieces containing Si, Al, Na and Ca in the paste is possible. Studies have shown that these unreacted pieces can be dissolved in distilled water

which could probably result to a reaction (Lee & Lee, 2015). Therefore RCA deriving from GPC should be considered as potentially alkali silica reactive.

- The RCA replacement level is still expected to be the most influencing parameter for the properties of the resulting mixes.

4 Methodology & experimental procedures

4.1 Brief in methodology

Based on the above commentary and the main literature findings, the below described project plan was established. The choice of the conducted tests was made regarding the distinct characteristics of GPC and the critical points for evaluation concerning its utilisation as RCA.

The investigated type of GPC was fly ash/slag based. This type was considered as appropriate for investigation due to its suitability for high volume applications. Additionally, the potential of using both OPC and GPC as "hosting matrices" was investigated. The testing was conducted on OPC and GPC mortars incorporating fine OPC and GPC FRCA. The replacement percentages of natural sand by FRCA were 0% (Reference mix), 25% (Low replacement level) and 50% (High-replacement level) by mass. The investigation of fine aggregate replacement was chosen because it is more unfavourable compared to coarse aggregate replacement. The FRCA were produced in the laboratory by casting pure GPC and OPC binder. This was considered as the optimum way to examine the influence of the paste type on FRCA and RAC properties without introducing additional parameters such as chemical composition and quality of the original aggregates. The compressive strength of the original material as well as density, water absorption and alkali-silica reactivity of FRCA were tested. The RAC mortar mixes were tested for compressive and flexural strength, water absorption and drying shrinkage, while density and flow were recorded.

The mix design for the mortars, described in detail in the following sections, was imposed by the standard for the evaluation of alkali silica reactivity of aggregates. It was decided to follow the same mix design for the production of all specimens to achieve homogeneity given it did not present significant differences with the suggested one for mortar testing. The proportions for GPC binder and mortar were based on the literature findings. The

conditioning of OPC and GPC specimens was conducted according to the following rationale: The existing standards specify moist curing conditioning of OPC by immersion in water in controlled temperature. Since this curing method does not favour the hardening process of GPC pastes, based on the literature findings it was decided to consider as corresponding moist conditioning the storage of GPC specimens in sealed plastic bags in controlled temperature. The specimens with OPCMatrix were kept in separate sealed plastic bags with water, submerged at the curing tank, while the GPCMatrix specimens were kept in separate sealed plastic bags in the conditioning chamber. The investigated mixes are presented in Table 1.

Table 1 Investigated mortar matrix – aggregates combinations

Mix combinations				
Mix Label	**Mortar Matrix**	**Proportions of fine aggregates**		
		NA	**OPC-RA**	**GPC-RA**
OPC_100%(REF)	Ordinary Portland Cement	100%	-	-
OPC_25%OPC		75%	25%	-
OPC_50%OPC		50%	50%	-
OPC_25%GPC		75%	-	25%
OPC_50%GPC		50%	-	50%
GPC_100%NA(REF)	Fly Ash-Slag Geopolymer Cement	100%	-	-
GPC_25%OPC		75%	25%	-
GPC_50%OPC		50%	50%	-
GPC_25%GPC		75%	-	25%
GPC_50%GPC		50%	-	50%

The notation used for the mixes follows the rational: **MortarMatrix_Replacement percentageType of aggregate**. For example, OPC_25%GPC means a mortar with OPC matrix and 25% replacement of sand by GPC-FRCA. The reference mixes with 0% replacement are labelled as **MortarMAtrix_100% NA.**

4.2 Materials

For the preparation of the specimens the following materials were used.

4.2.1 Ground Granulated Blastfurnace Slag (GGBS)

Ground Granulated Blastfurnace Slag (GGBS) was provided by the Hanson Heidelberg cement group from the Port Talbot works. Its chemical analysis is shown in Figure 1 . In the XRD pattern, the halo and the absence of distinct peaks which would correspond to impurities indicate it is highly amorphous.

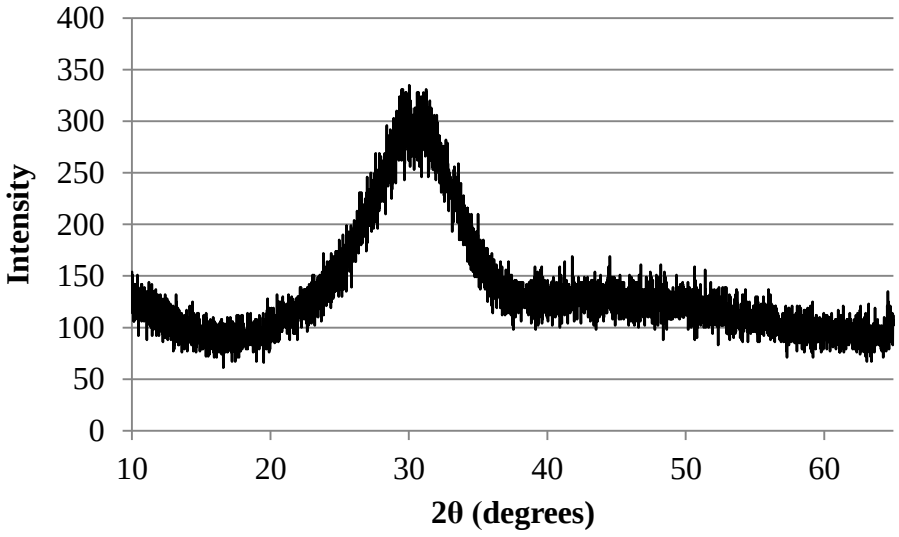


Figure 1 XRD pattern of GGBS

4.2.2 Fly Ash

The fly ash used was CEMEX 450-S (BS EN 450 - 1 Fineness Category S; LOI Category B) and its chemical composition is shown in Figure 2 .The chemical analysis was provided directly by the supplier and it is demonstrated Table 2.

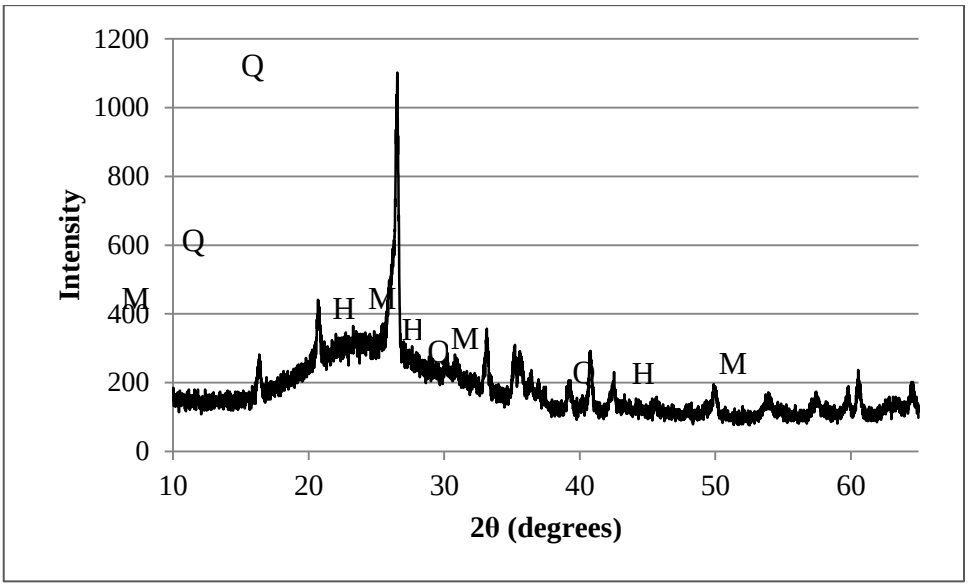


Figure 2 XRD pattern of FA (Q: quartz, H: hematite, M: mullite)

Table 2 Chemical analysis of precursors by X-Ray fluorescence

Constituents (wt %)	GGBS	FA
SiO_2	35.15	49
Al_2O_3	13.07	23.5
Fe_2O_3	0.28	8.7
CaO	39.6	2.4
MgO	8.47	1.4
SO_3	0.17	0.8
Na_2O	0.14	3.06
K_2O	0.51	0.87
TiO_2	0.66	
MnO	0.44	
P_2O_5		1.1
LOI	0.97	4.4

4.2.3 Sodium Hydroxide and Sodium Silicate

The sodium hydroxide used for the activating solution for the GPC was in the form of pellets and was supplied by Sigma-Aldrich (NaOH, 98-100.5%). The sodium silicate solution used for the production of the activating solution was supplied by Sigma Aldrich. The linear formula describing the chemical compound is: Na_2O (SiO_2) x xH_2O. The NaOH and Na_2O (SiO_2) x xH_2O were mixed with distilled water and cooled for one day before use. The sodium hydroxide used for the immersion solution for the ASR reactivity test was in the form of pearls and was supplied by Alfa Aesar (NaOH, 97%). It was mixed with distilled water to prepare the solution.

4.2.4 Portland cement

For the production of the Portland cement General Purpose Portland fly ash cement/ Sulfacrete EN 197-1 –CEMII/BV 32,5R supplied by Tarmac Cement & Lime Ltd was used. The information provided on the Declaration of Performance for the product by the manufacturer is presented in Table 3.

Table 3 Characteristics of Portland cement

Essential characteristics	**Performance**	Harmonised technical specification
Common cements (Subfamilies constituents and composition)	CEMII/B-V	EN 197-1:2011
Compressive strength (early and standard)	32,5R	
Setting time	Pass	
Loss in ignition	Pass	
Soundness • Expansion • SO_3 content	 Pass Pass	
Chloride content	Pass	
Supplementary information LOI of fly ash Min % fly ash	 <7% 25%	

4.2.5 Standard sand

Standard Sand conforming to the specification of Clause 5.1of BS EN196-1:2005 *Methods of testing cement* was used. The sand was pre-packed in bags of 1.350±5 g and its' particle size distribution is presented in Table 4.

Table 4 Particle size distribution of the CEN Reference sand

Square mesh size(mm)	Cumulative sieve residue (%)
2,00	0
1,60	7±5
1,00	33±5
0,50	67±5
0,16	87±5

4.3 Fabrication of samples and Testing procedures

4.3.1 Recycled aggregates

4.3.1.1 Casting

The recycled aggregates used in this study were produced in the laboratory by casting pure GPC and OPC binder. The casting took place in two batches for each binder using the pan mixer in Image 3 (Cretangle multi flow mixer, Type: SE/SPH) and 100x100x100 mm^3 cubes were produced with the use the plastic moulds.

Image 3 Cretangle multi flow pan mixer Type: SE/SPH

For the production of the GPC-RCA, fly ash/slag based GPC binder was used. The proportion of fly ash to slag was 50/50 by mass and the water to Geopolymer solids (w/s) ratio was 0.5. The molar ratio of SiO_2 /Na_2O used was 1. The concentration of Na_2O in the activating solution was 5% (Table 5).

Table 5 Mix design for fly ash/slag GPC binder for the production of GPC-RCA

Mix design of GPC binder	
FA/GGBS (by mass)	50/50
Concentration of Na_2O	5%
SiO_2/Na_2O	1
Water/GPC Solids	0.5

The first batch hardened in the mixer and its' pouring to the moulds was not possible. The hardened pieces of the binder where removed from the mixer vessel and kept in plastic bags in order to be used. It was decided not to dispose this batch because the incident was considered a good example of real-life conditions. Aggregates deriving from that paste could provide useful data for the weaknesses of GPC-FRCA. The casting of the second batch was successful and the paste was poured in the moulds. The amount of materials for each batch is demonstrated in Table 6.

Table 6 Amount of materials for one batch for GPC-RA casting

Material	Quantity (kg)
Fly ash	5.00
GGBS	5.00
Water	2.375
Sodium Hydroxide	0.330
Sodium Silicate	0.906

For the OPC-FRCA, OPC binder with w/c ratio 0.4 was casted. The amount of materials for each batch is presented in Table 7.

Table 7 Amount of materials for one batch for OPC-RCA casting

Material	Quantity(kg)
Portland cement	10
Water	4.00

All the specimens were demoulded 1 day after casting. During demoulding some of the GPC specimens were damaged. All the cubes as well as the pieces of hardened GPC paste were kept in sealed plastic bags to preserve constant humidity and were left to cure for 28 days at 20±5^{o}C.

4.3.1.2 Crushing & Testing procedures

After the end of the 28day curing period the compressive strength of the cubes was tested using the compression machine Automax 5 with 2000kN capacity, supplied by Controls (Image 4).

Image 4 Compression machine Automax 5

After the breaking of the GPC cubes, unreacted pieces of material were observed in the hardened paste, while nothing unusual was observed in the OPC paste (Image 5).

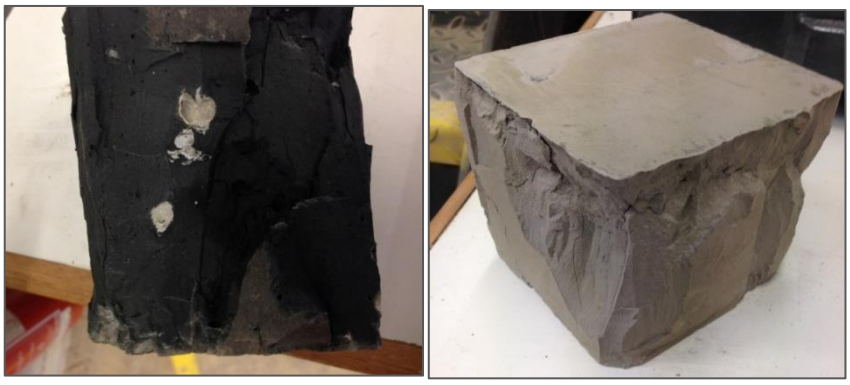


Image 5 Broken GPC &OPC binder cubes

After the compressive strength test was completed, the cubes were crushed using the rock crusher (Retsch, Type: BB200 Mangan) (Image 6) and sieved to produce fine recycled aggregate with the particle size distribution demonstrated in Table 8. The aggregates were kept in sealed plastic bags for the whole duration of the project.

Table 8 Particle size distribution for FRCA

Particle size(mm)	Percentage (%)
≥1	33±3
≤1 & ≥0.5	33±3
≤0.5	33±3

Image 6 Rock crusher

Following, the water absorption and density of the aggregates were tested. The test was conducted for the GPC-FRCA, OPC-FRCA and the Standard sand. The procedures were conducted in accordance with BS EN 1097-6:2013 *Test for mechanical and physical properties of aggregates*. Each aggregate sample was oven dried at 105 ± 5 _C until constant mass was achieved and then placed in the depicted pyknometers (Image 7) with water for 24±0,5h at 20±5^{o}C.

Image 7 Test for the density & water absorption of aggregates

The density and water absorption of the aggregates were calculated using the following formulas.

Apparent particle density: $$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)}$$

Oven-dried particle density: $$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)}$$

Saturated-surface dried particle density: $$\rho_{ssd} = \rho_w \frac{M_1}{M_1 - (M_2 - M_3)}$$

Water absorption after immersion for 24h: $$WA_{24} = \frac{100 * (M_1 - M_4)}{M_4}$$

Where:

ρ_w: density of water at the test temperature (20^{o}C for the specific test) (Mg/m^3)

M_1: mass of the saturated and surface dried aggregate in the air (g)

M_2: mass of the pyknometer containing the sample of saturated aggregate and water (g)

M_3: mass of the pyknometer filled with water only (g)

M_4: mass of the oven-dried test portion in air (g)

4.3.2 Mortar specimens

4.3.2.1 Casting

The GPC and OPC mortar specimens were produced based on the same mix-design presented in Table 9. No water compensation or presaturation of aggregates took place with the exception of the OPC_50% OPC mix, where extra water was added during mixing as the materials were too dry to mix.

Table 9 General Mix design for mortar specimens

Mix-design for OPC & GPC mortars	
Water/cement* ratio	0,47
Parts of binder by mass	1
Parts of sand by mass	2,25

*For the GPC the corresponding value is water/solids ratio

The geopolymer mortars were produced with the same fly ash and GGBS as the ones used for the GPC-FRCA. The proportion of fly ash to slag was 50/50 and the molar ratio of SiO_2 /Na_2O 1. The percentage of Na_2O in the activating solution to binder was reduced to 3 % (Table 10). This reduction took place to avoid the rapid hardening of GPC that occurred during the binder casting.

Table 10 Mix design for the fly ash/slag GPC mortar

Mix design of GPC binder	
FA/GGBS (by mass)	50/50
Percentage of Na_2O	3%
SiO_2/Na_2O	1

The Portland cement mortars were produced with the same cement as the OPC-FRCA.

To test the ASR reactivity of aggregates, 4 mortar bars of 25x 25 x250mm^3 for each mix were fabricated (Image 11). The amount of materials and the mix design are presented in Table 11. Some of the specimens were damaged during demoulding and the corresponding castings were repeated. Therefore the materials for each batch and not the overall amount are presented.

Table 11.Amount of materials for one batch for the casting of 4mortar bars

Mix	**Batch for 4 specimens (25x25x250mm^3)**							
	Parts of material per mass			**Amount of materials**				
	Binder	Fine aggregate	Water	Cement	Water	NA	OPC-RA	GPC-RA
OPC_100%NA	1	2.25	0.47	600	282	1,350	-	-
OPC_25%OPC	1	2.25	0.47	600	282	1,012.5	337.5	-
OPC_50%OPC	1	2.25	0.50	600	300	675	675	-
OPC_25%GPC	1	2.25	0.47	600	282	1,012.5	-	337.5
OPC_50%GPC	1	2.25	0.47	600	282	675	-	675
	Parts of material per mass			**Amount of materials**				
	Binder	Fine aggregate	Water	FA&GGBS	Solution	NA	OPC-RA	GPC-RA
GPC_100%NA	1	2.25	0.47	600	282	1,350	-	-
GPC_25%OPC	1	2.25	0.47	600	282	1,012.5	337.5	-
GPC_50%OPC	1	2.25	0.47	600	282	675	675	-
GPC_25%GPC	1	2.25	0.47	600	282	1,012.5	-	337.5
GPC_50%GPC	1	2.25	0.47	600	282	675	-	675

In total 8 mortar prisms of 40x40x160mm^3 (Image 12)were fabricated for each mix, of which 3 were used for the flexural and compressive strength test, 3 for the water absorption test and 2 for drying shrinkage measurement. The amount of materials corresponding to one batch for 3 specimens is presented in Table 12. For the casting of 2 prisms the amount of binder was reduced by 100 g and the corresponding quantities of sand and water were calculated using the presented proportions.

Table 12 Amount of materials for one batch for the casting of 3 mortar prisms

Mix	Batch for 3 specimens (40x40x160mm^3)							
	Parts of material per mass			**Amount of materials(g)**				
	Binder	Fine aggregate	Water	Cement	Water	NA	OPC-RA	GPC-RA
OPC_100%NA	1	2.25	0.47	450	212	1.013	-	-
OPC_25%OPC	1	2.25	0.47	450	212	760	253	-
OPC_50%OPC	1	2.25	0.50	450	250	506.5	506.5	-
OPC_25%GPC	1	2.25	0.47	450	212	760	-	253
OPC_50%GPC	1	2.25	0.47	450	212	506.5	-	506.5
	Parts of material per mass			**Amount of materials**				
	Binder	Fine aggregate	Water	FA&GGBS	Solution	NA	OPC-RA	GPC-RA
GPC_100%NA	1	2.25	0.47	450	212	2,025.00	-	-
GPC_25%OPC	1	2.25	0.47	450	212	760	253	-
GPC_50%OPC	1	2.25	0.47	450	212	506.5	506.5	-
GPC_25%GPC	1	2.25	0.47	450	212	760	-	253
GPC_50%GPC	1	2.25	0.47	450	212	506.5	-	506.5

The recycled aggregate was mixed with the standard sand according to the specified proportions for each mix. A representative example of the resulting aggregate can be seen in Image 8.

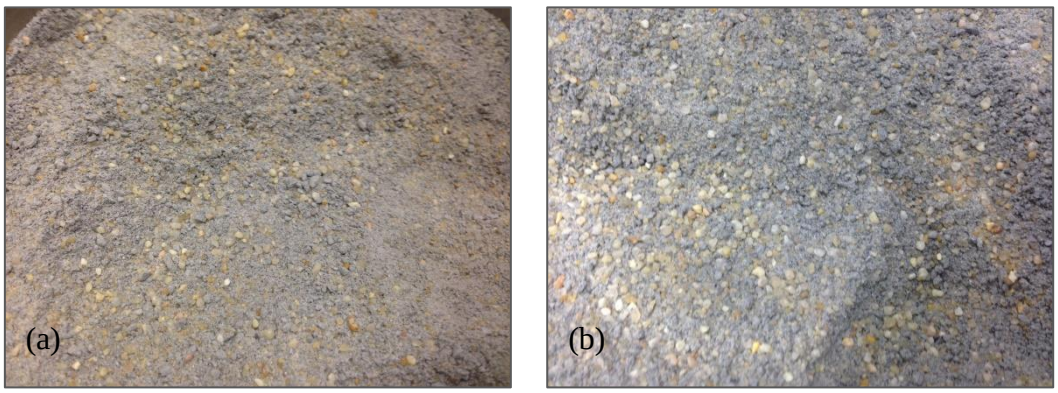


Image 8 Mixed sand with (a) 50% replacement by OPC-RCA, (b) 50% replacement by GPC-RCA

The mortars were mixed using either the automatic (Automix, Automatic programmable mixer, Controls) or the manual (Test international) mortar mixer (Image 9). The mixing was operated according to the procedure described in Clause 6 of BS EN 196-1:2005 *Methods for testing cement.*

Image 9 (a) Controls Automix, Automatic programmable mortar mixer, (b) Test International, manual mortar mixer

For the casting of the mortar bars for the ASR reactivity of aggregates, specially fabricated moulds were used. They were made of plywood with plastic partitions and each mould allowed the fabrication of 4 specimens. Holes of 2mm diameter were drilled at the edge of the moulds to allow the input of steel nails. These nails performed as studs for the measurement of the specimen's length and were placed in the moulds before the pouring of the mortar as shown in Image 10. For the preparation of the mortar prisms the standardised steel moulds were used. The paste was poured in the moulds in two layers and after the application of each layer vibration for 30s seconds using the vibrating table took place.

Image 10 Arrangement of moulds for the fabrication of mortar bars

Image 11 Mortar bas for alkali silica reactivity testing

Image 12 Mortar prisms

4.3.2.2 Testing procedures

Flow test

After the mixing was completed the flow of each mortar was tested according to the procedure described in Clause 9 of BS 4551-1:1998 *Methods of testing mortars, screeds and plasters*. This comprises 25 drops of the flow table in Image 13 within 15s

Image 13 Flow table and mould

The flow was calculated as the resulting increase in average diameter of the mortar, measured on four diameters at equal intervals, expressed as a percentage of the internal base diameter of the mould.

Flexural & Compressive strength

The test in flexure and compression was conducted in accordance with BS EN 196-1:2005 *Methods of testing cement*. The specimens were demoulded 24±2h after casting and then kept in moist conditions for 28 days at 20±3^{o}C. Moist conditions for each type of matrix are considered those described in "4.1Brief in methodology" section. After the end of the curing period the prisms were removed from the moist conditions at about 15mins before the test was conducted. The Dartec Universal testing machine with 100KN capacity was used. A displacement control was preferred to the load control indicated by the standards, because the specific machine has been proved to provide more reliable results with that

method. The used displacement rates provided results corresponding to the load rates indicated by the standard method for each test.

The test for flexural strength was conducted using the three-point loading method with the apparatus in Image 14 . The machine was set at an automatic displacement control of 0,2mm/min corresponding to load rate of about 50±10N/s until fracture.

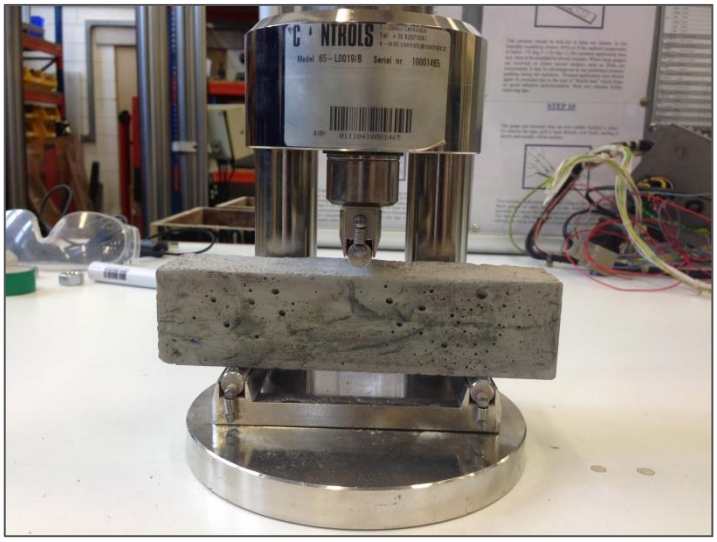


Image 14 Three-point loading apparatus used for the flexural strength testing of mortar prisms

The results were recorded automatically and the flexural strength was calculated using the formula:

Flexural Strength:

$$R_f = \frac{1,5 * F_f * l}{b^3}$$

Where:

Rf: flexural strength (MPa)

b: the side of the square section of the prism (mm)

Ff: the load applied to the middle of the prism at fracture (N)

l :the distance between the supports (mm)

Compressive strength

The compressive strength test was carried out on the halves of the prisms used for the flexural strength test with the apparatus in Image 15 with an automatic displacement control of 0,5mm/min corresponding to a load rate of 2400±200 N/s.

Image 15 Apparatus used for the compressive strength testing of mortar prisms

The results were recorded automatically and the compressive strength was calculated using the formula:

Compressive Strength:

$$R_c = \frac{F_c}{1600}$$

Where:

Rc: the compressive strength (MPa)

Fc: the maximum load at fracture (N)

1600: the area of the platens or the auxiliary plates (40mmx40mm) (mm2)

Water Absorption

The water absorption test was carried out according to the method described in BS 1881-122:2011 *Testing concrete*. The specimens were demoulded 24±2h after casting and their surfaces were cleaned from any releasing reagent. They were kept in moist conditions identical to those described in the "Brief in methodology". At the age of 24 days the prisms were removed from moist conditions and placed at the oven at 105±5^{o}C for 72±2h. They were removed from the oven and left to cool in airtight-sealed plastic boxes for 24h. After the end of the cooling period, the mass of the oven-dried prisms was recorded and then they were immersed in water for 30min. Upon removal from water the mass of each specimen was recorded. The water absorption was calculated according to the formula below.

Water absorption:

$$WA = \frac{M_{wet} - M_{dry}}{M_{dry}} * 100$$

Where:

WA: Water absorption after 30min of immersion in water (%)

M_{wet}: mass of the specimen after 30 min of immersion in water (g)

M_{dry}: mass of oven-dried specimen (g)

Drying Shrinkage

The procedure for testing the drying shrinkage of the specimens was based on that described in BS ISO 1920-8:2009 *Testing of concrete* but some alterations were made. Two prismatic specimens for each mortar mix were tested. The specimens were demoulded 24±2h after casting and then kept in moist conditions identical to those described in the "Brief in methodology" section for a period of 7days. After the end of moist curing period they were left to dry at 20±5^{o}C. In order to measure the length changes of the prisms a 100mm digital DEMEC strain gauge was used (Image 16). On the day of removal from moist conditions , pre-drilled stainless-steel discs were attached using a setting-bar, at opposite facing sides of each specimen with a suitable adhesive and the initial reading was

taken. After that, the length change was measured after total periods of air drying of 7, 14, 21 and 28 days.

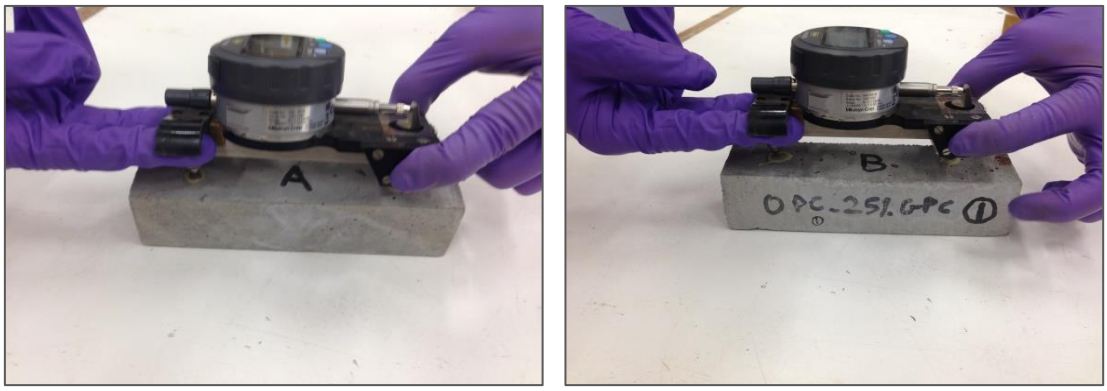


Image 16 Measurement of length change due to drying shrinkage with the digital Demec gauge

According to the manufacturer one division corresponds to 8.07 microstrains for the 100mm gauge, so the final shrinkage was calculated according to the formula below.

Drying Shrinkage: $S_n = (R_{Initial} - R_n) * 8,07 * 10^3$

Where:

Sn: Drying shrinkage after n days of air drying

$R_{Initial}$: Initial reading of gauge

R_n: Reading of gauge at n days of air drying

Alkali-silica reactivity of aggregates

The testing procedure was conducted according to an under development method the DD 249:1999 *Testing aggregates-Method for the assessment of alkali silica reactivity-Potential accelerated mortar-bar method*. The particular method suggests an accelerated procedure and was chosen due to its short duration (16 days) compared to other standard methods. The casting for the mortar bars was repeated twice as the first specimens were damaged during demoulding. This proved it was not possible to demould the bars 1 day after casting, as indicated by the method, without damaging, due to weakness of the mortars and the layout of the moulds. Therefore, the bars were demoulded 2 days after casting. Right after demoulding the nails ejecting from the bars were cut in appropriate

length to allow the specimens to fit the length comparator and the bars were submerged in distilled water in airtight sealed plastic boxes in the oven at 80^{o}C for 24±2h. After the end of the 80^{o}C curing period the specimens were removed from the oven and the initial reading was taken. Then, they were immerged in 1M NaOH solution in the plastic airtight sealed boxes and placed in the oven at 80±2^{o}C. The first measurement was taken after 1 day of immersion in NaOH solution and the following after 7 and14 days. The length measurements were conducted using the depicted digital length comparator (Image 17) and a 259mm reference metallic bar. In order to satisfy the method's requirement, that the solution should have access to all the surfaces of the bars and a distance of at least 5mm from the bottom, a special racking arrangement was used (Image 18).

Image 17 Length change measurement of mortar bars due to Alkali silica Reaction

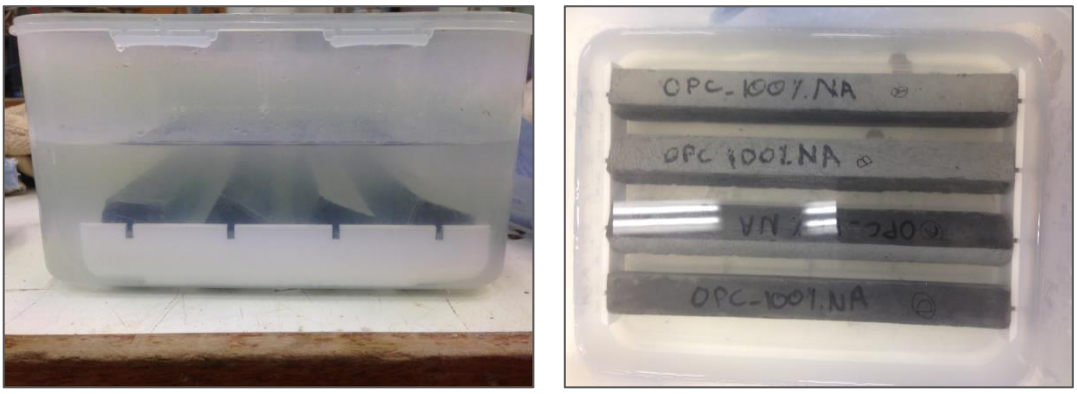


Image 18 Racking for Alkali Silica Reaction testing mortar bars

5 Results & discussion

5.1 Recycled Aggregates

5.1.1 Introduction

The data of the aggregate testing and the analysis of the results in comparison with the literature findings are presented in the following sections.

5.1.2 Strength of original material

In Table 13the compressive strength of the original binder is presented, as determined by the compression test of the 100x100x100 mm^3 cubes.

Table 13 Compressive strength of OPC &GPC binder cubes

Specimen No	GPC Cubes		OPC Cubes	
	Compressive Force [kN]	Compressive Strength [MPa]	Compressive Force [kN]	Compressive Strength [MPa]
1	332.20	33.19	472.90	47.29
2	333.74	33.37	477.80	47.76
3	577.30	57.65	479.00	47.88
4	485.00	48.30	466.70	46.66
5	532.50	53.25	485.60	48.55
6	474.80	47.48	458.20	45.79
7	-	-	479.40	47.93
8	-	-	496.70	49.67
9	-	-	493.40	49.34
10	-	-	474.30	47.37
Average	455.92	45.54	478.40	47.82
Standard Deviation	93.13	9.29	10.98	1.11

It is observed that both materials demonstrate high average strength, around 50 MPa, which was expected given the low c/w ratio of the binders and the high alkalinity of GPC

binder. The large deviation demonstrated by the results for GPC cubes is attributed to the damaging of a part of the specimens. The damaged specimens presented significantly lower values but it was considered more realistic to include them. Despite that, it could be said that the compressive strength for GPC binder lies at 47-57MPa.

5.1.3 Density & Water Absorption

In Table 14 the results for the fine aggregate density and water absorption are presented.

Table 14 Water absorption & Density of FRCA

Aggregate Type	Apparent particle density ρ_a (kg/m^3)	Oven-dried particle density ρ_{rd} (kg/m^3)	Saturated-surface dried particle density ρ_{ssd}(kg/m^3)	Water Absorption, W_{24} (%)
NA	2,631.28	2,202.19	2,367.37	7.39
OPC-RCA	2,247.58	895.97	1,497.87	67.01
GPC-RCA	2,041.71	1,151.28	1,588.29	37.82

It is observed that OPC-FRCA and GPC-FRCA demonstrated 14.5% and 22.5% lower density compared to natural sand correspondingly. For GPC ρa is lower compared to OPC, while the opposite is observed for ρ_{rd} and ρ_{ssd}. The WA of both FRCA is significantly higher than that of the natural sand and its effect on the mortars was apparent during mixing. GPC-FRCA demonstrates a value 5 times that of FNA, while for OPC-FRCA the value is almost 10 times higher.

The obtained values for density are slightly lower than those found in literature, while WA was significantly higher. Generally ρrd and ρssd at the range of 1,970-2,140 kg/m^3 and 2,190-2,320kg/m^3 correspondingly were reported (Dhir, et al., 1999; Wai , et al., 2012; Silva, et al., 2014a; Hansen, n.d.). The general trend for RCA WA is to be 3-6 times higher than that of NA with FRCA presenting values at the range of 8-12% (Akash Rao, 2007; Hansen, n.d.).

Density and WA of FRCA depend mainly on the adhered cement paste which increases with decreasing particle size. The nature of the original material (pure binder without aggregates) and the fineness to which FRCA was crushed are probably the parameters

responsible for the resulting values. Another parameter that possibly influenced the results is that the OPC-FRCA started setting after the 1day immersion in water. Considering the fact that this FRCA derived from a 2month old paste, this reaction is probably a result of incomplete hydration at the first stage.

5.1.4 Alkali-Silica reactivity

The results of the test for the evaluation of the alkali silica reactivity of the FRCA are presented in Table 15 and Table 16.

Table 15 Mean expansion of OPCMatrix mortar prisms after 14days of immersion in NaOH solution for the evaluation of the alkali silica reactivity of FRCA

OPC Mortar Matrix		
Mix	**Mean % expansion after immersion in NaOH solution for 14days**	**Standard deviation**
OPC_100%NA-REF	-0,028	0,012
OPC_25%OPC	0,061	0,011
OPC_50%OPC	0,034	0,063
OPC_25%GPC	0,041	0,008
OPC_50%GPC	0,060	0,009

Table 16 Mean expansion of GPCMatrix mortar prisms after 14days of immersion in NaOH solution for the evaluation of the alkali silica reactivity of FRCA

GPC Mortar Matrix		
Mix	**Mean % expansion after immersion in NaOH solution for 14days:**	**Standard deviation**
GPC_100%NA-REF	0,036	0,012
GPC_25%OPC	0,098	0,022
GPC_50%OPC	0,056	0,027
GPC_25%GPC	-0,066	0,014
GPC_50%GPC	-0,041	0,025

The criteria used to classify the potential expansivity of a set of specimens due to ASR of aggregates at 14days are presented in Table 17.

Table 17 Classification criteria of the potential expansivity of a set of specimens due to ASR of aggregates at 14days, *Data Source*: DD249:1999

Classification	Mean % expansion after immersion in NaOH solution for 14days
Innocuous	<0.10
Inconclusive (other assessment required)	0.10 to 0.20
Potentially expansive	>0.20

It is observed that none of the OPCMatrix specimens demonstrated expansion indicating potential alkali-silica reactivity of the FRCA. With the exception of OPC_100% NA mix, which exhibited shrinkage, all the specimens presented particularly low expansion percentages at the range of 0.03% to 0.06%. Although RCA deriving from GPC were considered prone to induce expansive ASR, the results for OPCMatrix mortars indicate the opposite.

For the GPCMatrix specimens the results are somehow different. Only, the GPC_25%OPC mix presented an expansion close to the limit of 0.10%. The reference mix and the one with 50% replacement of OPC-RCA, presented low expansion values while the mixes with GPCMatrix and GPC-RCA exhibited shrinkage.

Since the method was formulated for OPC mortars with low alkali content, the expansion exhibited by the OPCMatrix specimens will be considered as a more reliable criterion. As mentioned above, the results appear to be encouraging for the use of FRCA deriving from GPC mortar. Nonetheless, it is mentioned in the principles of the standard that the specific method should be used only to provide indicative results in advance of and in addition to those obtained by the BS 812-123:1999 *Testing aggregates- Method for determination of alkali-silica reactivity- Concrete prism method*. Any expansions obtained by the test should be corroborated whether using the aforementioned test or by the microscopic examination of the specimens. Also studies assessing the ASTMC 1260-2014 method, which is identical to DD249:199 used in the present study, report that accelerated methods

have been proved prone to provide a high percentage of false negative and positives [1] (Lenke & Malvar , 2009) due to their aggressiveness and the high dependence of results on the alkali content of the used cement. Additionally, in a study investigating the efficiency of existing accelerated methods for ASR detection, it is mentioned that their application on RCA presents shortcomings and it is preferable to use it as a screening method (Gress , et al., 2000). Although no definite conclusion can be drawn for the ASR reactivity of GPC-RCA at this stage, the preliminary conclusions is that they can be characterised as not potentially reactive.

The evolution of the specimens' length is presented in Figure 3 and Figure 4.

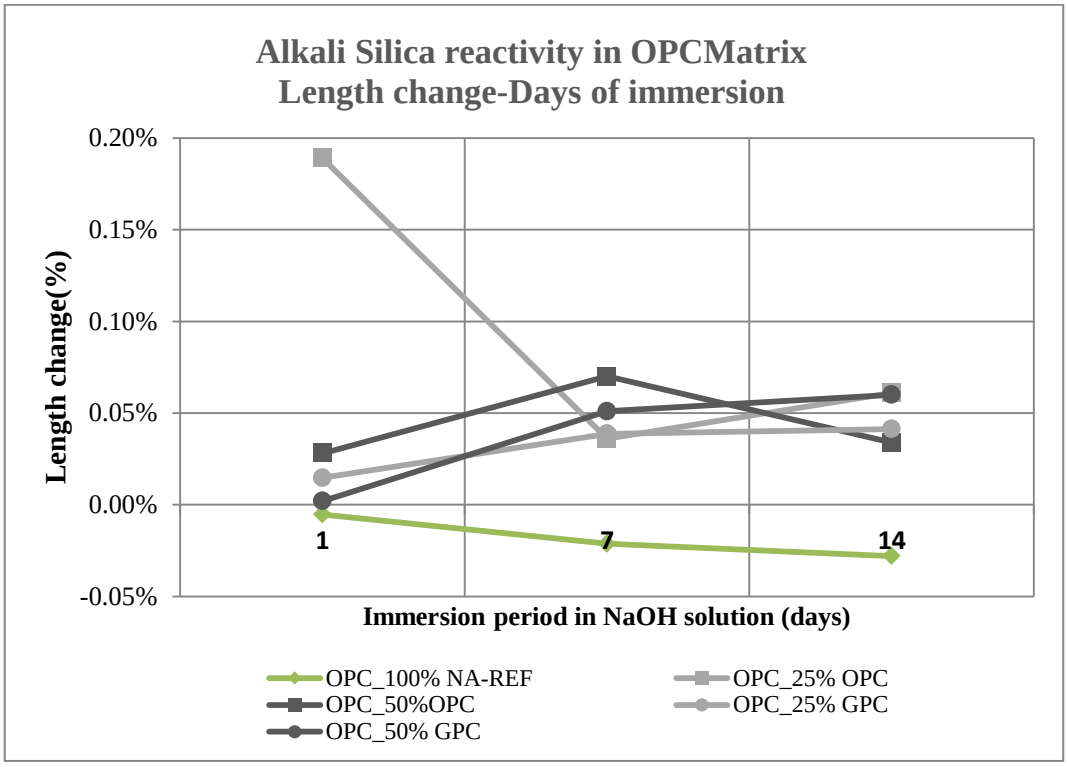


Figure 3 Mean % expansion of OPCMatrix mortar prisms during the immersion period in NaOH solution for the evaluation of the Alkali Silica reactivity of FRCA

The shrinkage presented by the reference mix is not considered as unusual since the incorporated aggregate is not reactive. It is possible that the alkaline solution affected the matrix or that usual shrinkage during OPC setting occurred. The sharp length increase and drop demonstrated by OPC_25%OPC could be attributed either to measurement mistake or thermal and chemical effects. Given the fact that OPC_50%OPC length presents ups and

[1] *False negative*: The method predicts no failure but field specimens show failure
False positive: The method predicts failure but field specimens show no failure

downs during the immersion period it is possible that mixes with OPC-FRCA are somehow influenced by the test conditions. The length change of the mixes with GPC-FRCA follows a gradual increase.

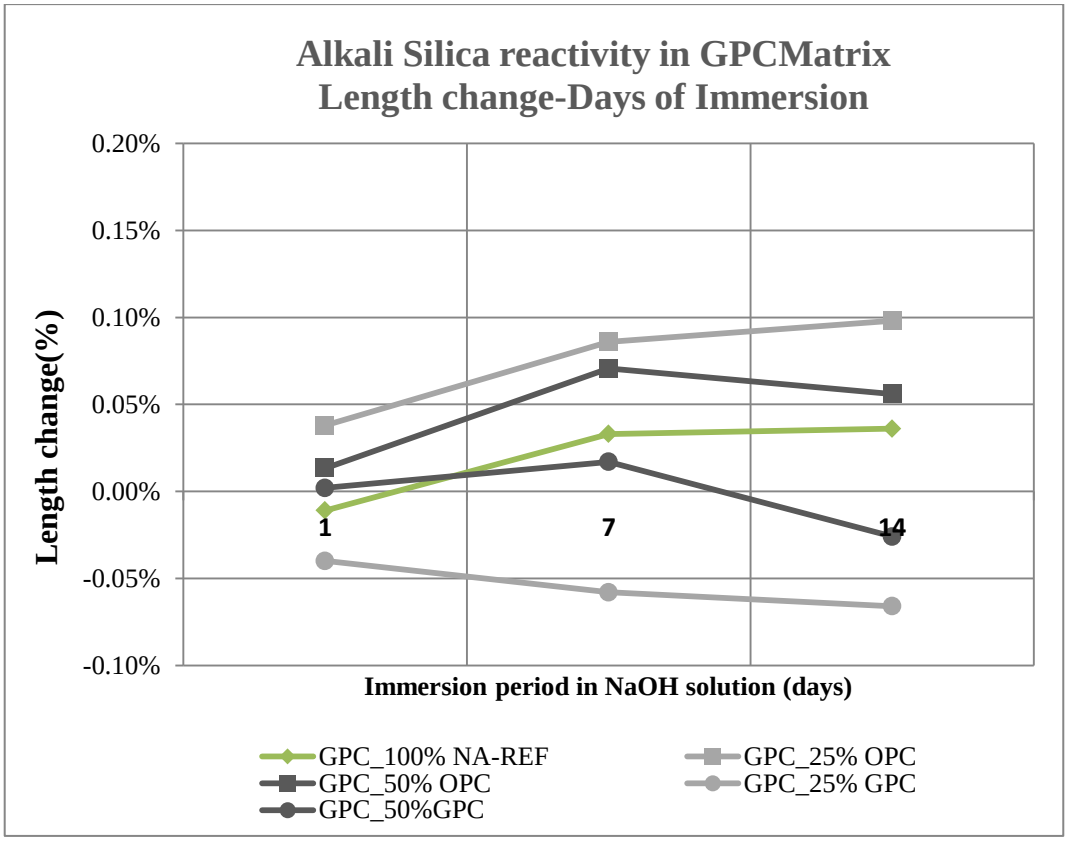


Figure 4 Mean % expansion of GPCMatrix mortar prisms during the immersion period in NaOH solution for the evaluation of the Alkali Silica reactivity of FRCA

The GPC_100%NA and GPC_25%OPC exhibited gradual expansion. The GPC_50%OPC and GPC_50% GPC expanded at the first 7 days and then exhibited shrinkage. The GPC_25%GPC followed a gradual downward trend throughout the whole immersion period. No clear influence trend of replacement percentage or aggregate type could be identified to justify the specimens' behaviour. The combination of heat and immersion in NaOH is likely to have affected the GPCMatrix, since according to literature the behaviour and properties of GPC depend significantly on temperature and moisture during curing. The immersion in NaOH solution could have activated parts that remained unreacted after mixing. Nonetheless it is evident that OPC and GPC FRCA had a distinct effect on the mortar.

Although the method examines only the 14day expansion, the length-change trends were considered as an interesting source of information for the mixes' behaviour. Considering the results, it could be concluded that the effect of each aggregate type is quite distinct on the two matrices. The influence of the replacement percentage is not clear though. Only a microscopic examination of the structure and reaction products in the mortars could provide a solid ground to analyse their behaviour.

Finally a noteworthy observation was made after the completion of the test. A white coloured substance resembling to a gel was found in the immersion solution of mixes incorporating GPC either in their matrix or as FRCA. Due to the limited time available it wasn't possible to analyse the chemical composition of the substance. Nonetheless it is considered as an indicator of an occurring chemical reaction that requires further investigation.

5.2 Mortar Mixes

5.2.1 Introduction

The results of the mortar testing are presented and discussed in the present chapter. The data was evaluated in relation to replacement percentage and aggregate type.

5.2.2 Flow & Workability

The results for the flow test of the mixes in relation to the FRCA replacement are presented in Figure 5.

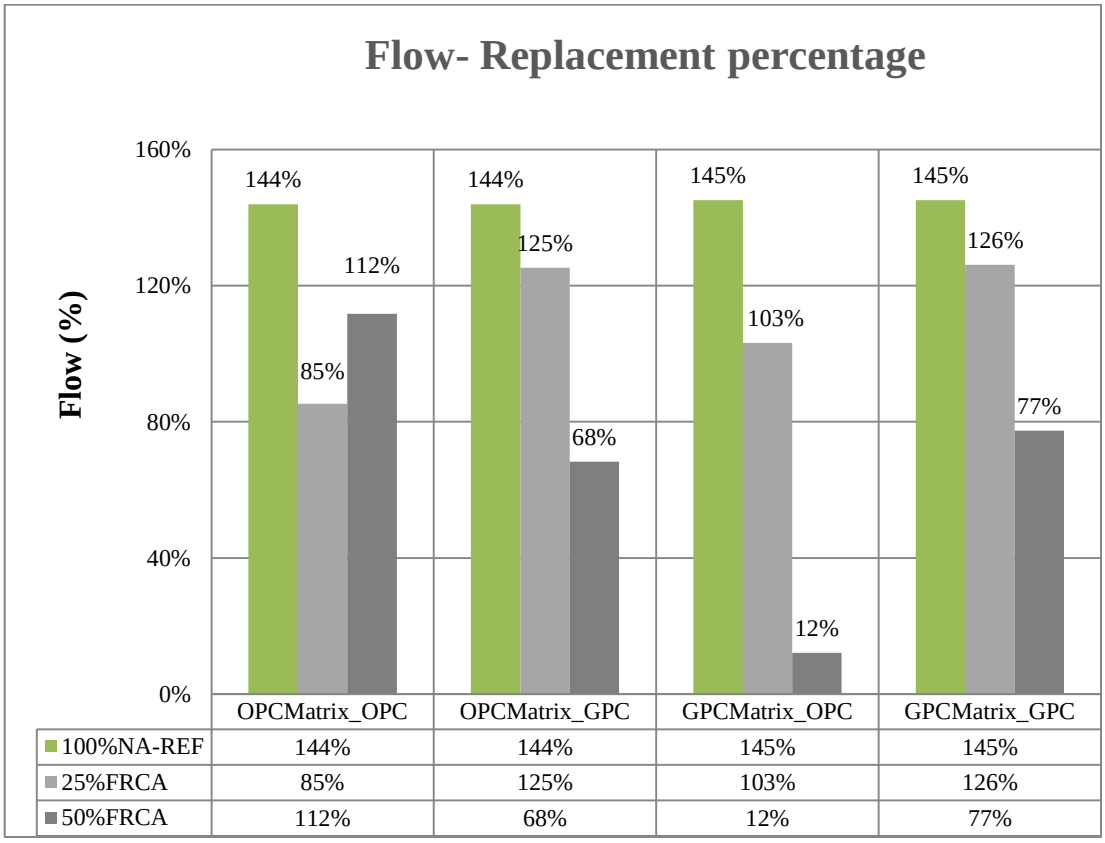


Figure 5 Flow test results in relation to replacement percentage of FRCA for all mixes

The notation in the graph is **Matrix Type _Aggregate Type.** The same notation is used at the following graphs as well.

It is apparent that the flowability decreased with increasing FRCA content. Compared to the reference mix, the reduction for 25% FRCA was 41%, 13%, 29% and 13% for the OPCMatrix_OPC, OPCMatrix_GPC, GPCMatrix_OPC and GPCMatrix_GPC accordingly. With rise of the replacement percentage up to 50%, the reduction in flow was

22%, 53%, 92% and 47% respectively. The anomaly for the OPC_50%OPC mix is due to the addition of extra water during mixing. Although the water addition makes the results incomparable, the necessity of this was actually indicative of the severe effect of the 50% OPC-FRCA addition on water demand during mixing.

The results for the flow test of the mixes in relation to aggregate type are presented in Figure 6.

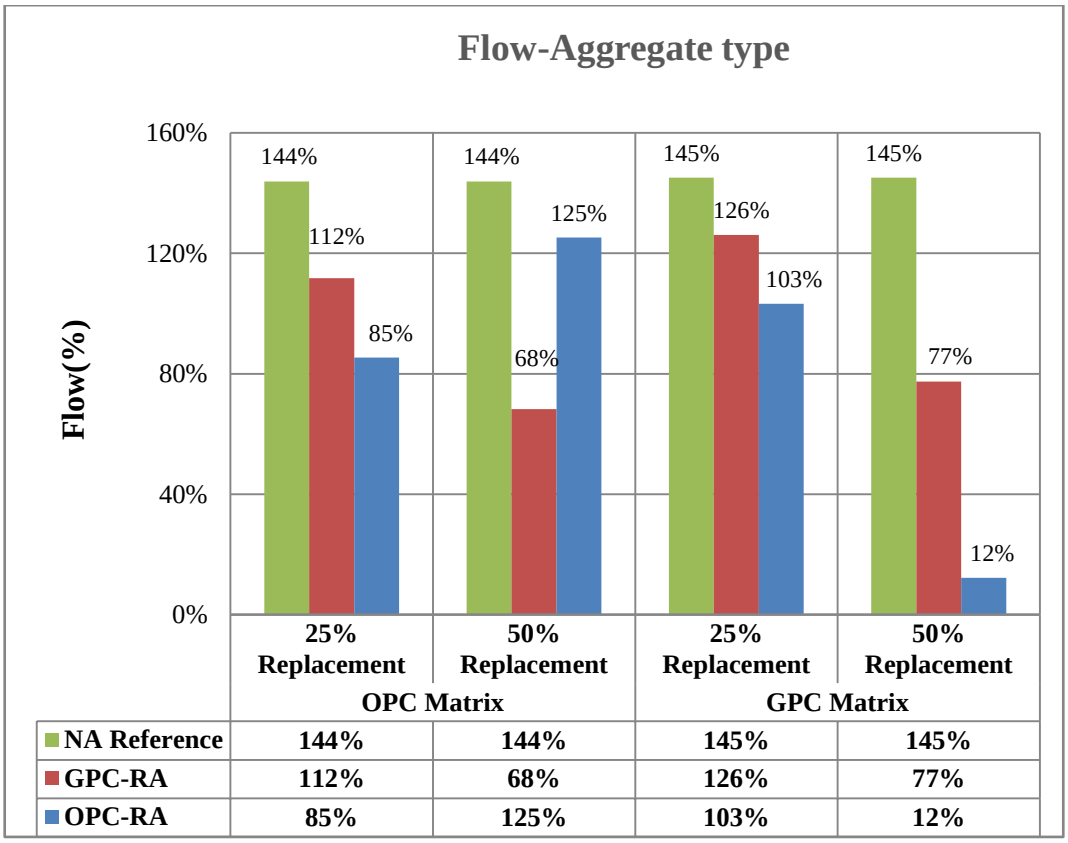


Figure 6 Flow test results in relation to type of FRCA for all mixes

It is observed that the GPC-FRAC had a less severe effect on the flow of mortars. For equivalent replacement percentages, mixes incorporating OPC-FRCA presented much larger reduction of flow compared to those with GPC-FRCA.

For the OPCMatrix specimens and 25% replacement, GPC-FRCA and OPC-FRCA caused reductions of 13% and 41% correspondingly. For double replacement percentage GPC-FRCA resulted in a reduction of 53%, while for OPC-FRCA mixing was not possible at the given w/c ratio.

In GPCMatrix mixes for 25% replacement, the reduction caused by OPC-FRCA (28%) is almost double that due to GPC-RA (12%). For 50% replacement the effect of OPC-RA on GPCMatrix was detrimental leading to 92% reduction of flow. The corresponding reduction with GPC-FRCA was a 46%.

For all aggregate-matrix combinations the increasing replacement percentage led to greater effect on workability. The results were in accordance with the literature findings since, similar effects were observed in flow for high replacement percentages in the overviewed studies (Akash Rao, 2007; Evangelista & de Brito, 2007). For 25% replacement however the reductions were not negligible as mentioned in literature (Paine & Dhir, 2010), but mixes were sufficiently workable. The decrease in flow was expected since both FRCA demonstrated significantly high WA compared to FNA. The greater impact of OPC-FRCA compared to GPC_FRCA is attributed to its WA and its tendency to react further when being in contact with water.

A noteworthy observation made during the test is that mixes with GPC matrix or aggregate resented thixotropic behaviour. A visual estimation of the RAC mortars' workability can be obtained by the pictures in Image 19.

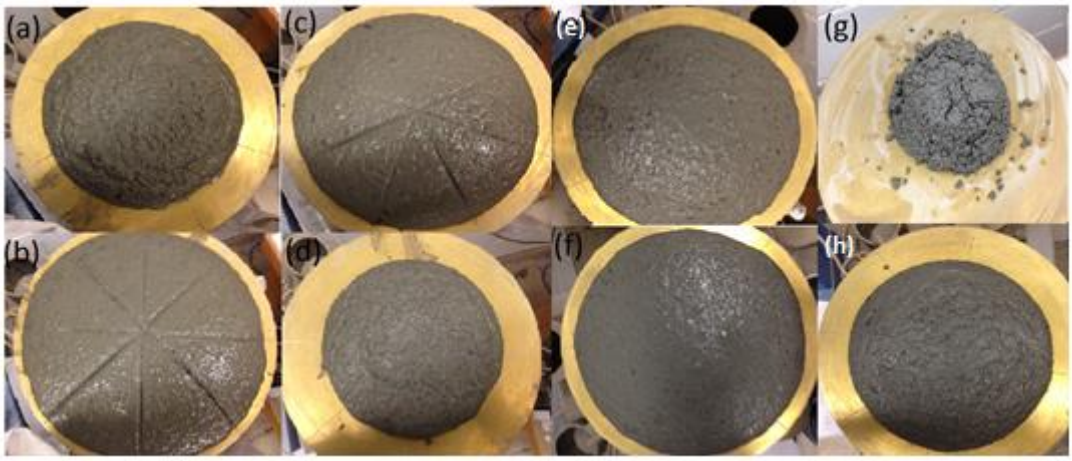


Image 19 Flow measurement of :(a) OPC_25%OPC-RA, (b) OPC_25%GPC-RA, (c) OPC_50%OPC-RA, (d) OPC_50%GPC-RA, (e) GPC_25%OPC-RA, (f) GPC_25%GPC-RA, (g) GPC_50%OPC-RA, (h) GPC_50%GPC-RA

5.2.3 Density

The mass of the specimens was recorded after demoulding, at oven drier and saturated condition. The mean mass was used for the results in Table 18.

Table 18 Density of mortar specimens

OPC Mortar Matrix		**GPC Mortar Matrix**	
Mix	**Density(kg/m^3)**	**Mix**	**Density(kg/m^3)**
OPC_100%NA-REF	2163,85	GPC_100%NA-REF	1948,78
OPC_25%OPC	2042,10	GPC_25%OPC	1990,67
OPC_50%OPC	1919,05	GPC_50%OPC	1798,18
OPC_25%GPC	2078,99	GPC_25%GPC	1876,52
OPC_50%GPC	1893,88	GPC_50%GPC	1898,22

It is observed that the density of mortar specimens is decreasing with increasing replacement levels. This was expected since FRCA have lower density compared to natural sand due to the hardened cement paste. For 50% replacement the demonstrated reduction was at about 12% for OPCMatrix and both types of aggregate, while for GPCMatrix the OPC-FRCA and GPC-FRCA lead to 7% and 2% reduction.

5.2.4 Compressive Strength

The values obtained from the compressive strength test at 28 days are presented in Table 19[2].

Table 19 Compressive strength values at 28 days

Compressive strength at 28days(MPa)					
Specimen No	**OPC_100%NA-REF**	**OPC_25%OPC**	**OPC_25%GPC**	**OPC_50%OPC**	**OPC_50%GPC**
1	35,77	37,37	37,97	35,06	38,07
2	31,47	40,20	39,25	39,70	32,92
3	35,45	40,83	36,29	35,46	33,18
4	34,35	46,71	42,13	37,69	34,97
5	36,66	44,36		36,93	34,17
6	41,80				37,61
Mean value	35,92	41,89	38,91	36,97	35,15
Standard Deviation	3,10	3,28	2,13	1,67	2,02
Specimen No	**GPC_100%NA-REF**	**GPC_25%OPC**	**GPC_25%GPC**	**GPC_50%OPC**	**GPC_50%GPC**
1	21,24	12,54	34,65	10,93	33,76
2	26,18	12,43	34,92	12,57	40,98
3	26,48	13,13	36,92	12,02	39,35
4	20,35	11,67	37,31	11,66	41,44
5	24,27	12,61	33,43	11,33	31,26
6	26,38	11,66	34,51	10,86	
Mean value	24,15	12,34	35,29	11,56	37,36
Standard Deviation	2,50	0,53	1,38	0,60	4,10

[2] Values presenting large deviation from the mean compressive strength were excluded from the final results

The mean compressive strength of the mixes at 28days in relation to the FRCA replacement levels is presented in Figure 7.

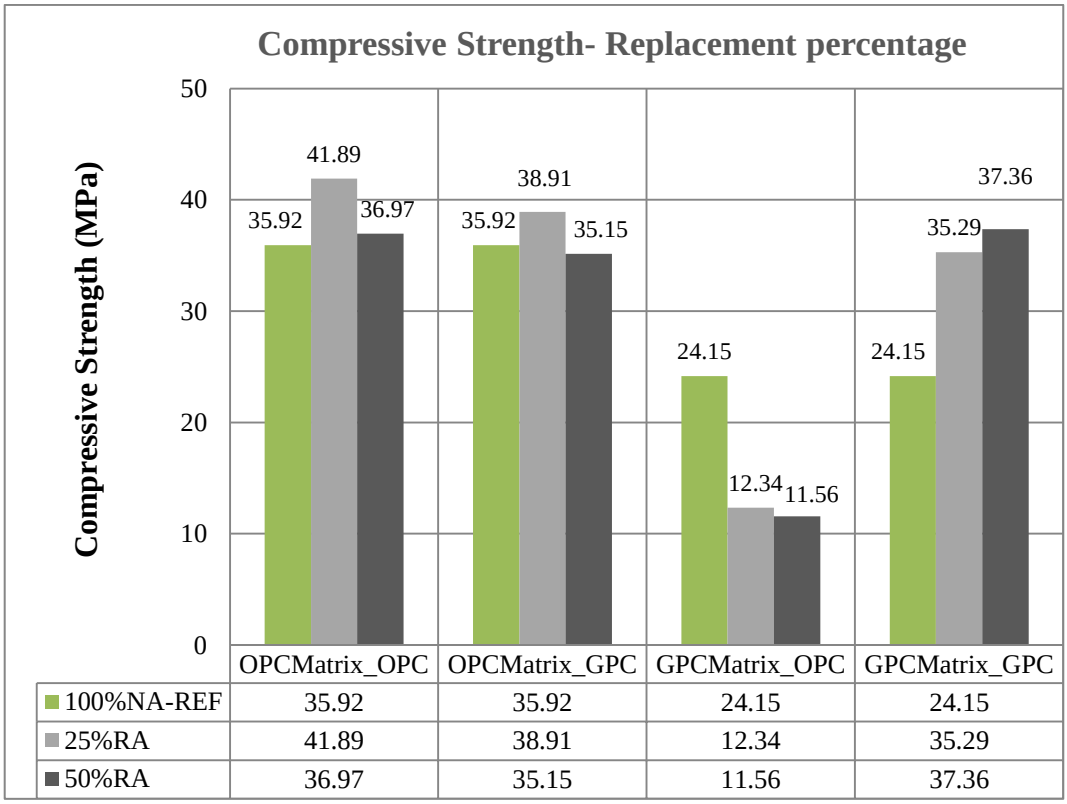


Figure 7 Mean Compressive strength results for all mixes in relation to replacement percentage of FRCA

A variation in the behaviour of each matrix-aggregate type combination is observed in the results for the compressive strength.

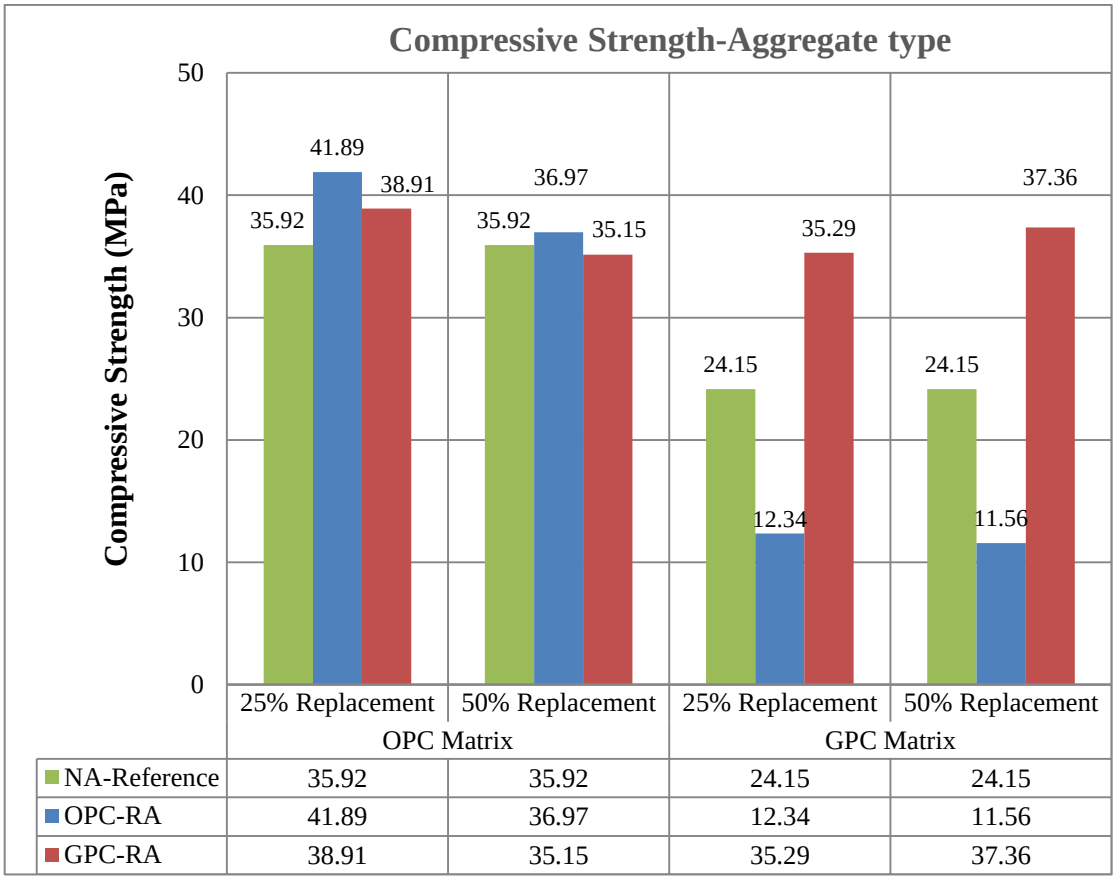
The effect of replacement on the compressive strength of the OPCMatrix could be characterized as negligible. For 25% FRCA an increase of 14% for the OPC–FRCA and 7% for the GPC-FRCA compared to the reference was observed. For double replacement level the obtained values presented a difference of 2% from the reference. It should be noted that the strength of OPC_50% OPC was probably enhanced by the addition of water.

The GPCMatrix mortars responded in a completely opposite way to the replacement, which seemed to have a more intense effect on them in comparison to OPCMatrix mixes. With the use of OPC-FRCA the strength was reduced in half for low replacement level and decreased slightly more for high replacement percentage (49% and 52% reductions compared to the reference for 25% and 50% replacement correspondingly). The addition of

GPC-FRCA on the other hand led to a 32% increase for 25% replacement and 35% for 50% replacement.

According to the above remarks, it could be concluded that for the specimens investigated on this project, replacement percentage is not a major influencing parameter. Specifically, OPCMatrix mixes did not appear to be significantly affected by the increase of FRCA even though increasing replacement led to slightly decreased strength. For GPCMatrix mixes the values for low and high replacement percentage do not differ more than 5% although the influence of each aggregate type is different.

Following, the correlation between the type of FRCA and mean compressive strength values is presented in Figure 8.



	25% Replacement (OPC Matrix)	50% Replacement (OPC Matrix)	25% Replacement (GPC Matrix)	50% Replacement (GPC Matrix)
NA-Reference	35.92	35.92	24.15	24.15
OPC-RA	41.89	36.97	12.34	11.56
GPC-RA	38.91	35.15	35.29	37.36

Figure 8 Mean Compressive strength results for all mixes in relation to type of FRCA

As it was indicated by the previous graph the effect of FRCA on compressive strength of the mixes investigated on the present study, appears to be mainly depended on the interaction between the matrix and aggregate material and secondarily on the replacement levels.

It is observed that the effect of FRCA was marginal for the OPCMatrix mortars regardless the aggregate type and replacement percentage. For 25% replacement the mix with OPC-FRCA demonstrated 7%higher value compared to that incorporating GPC-FRCA. For 50% the result for OPC-FRCA mix is 5% higher than the corresponding with GPC-FRCA but the addition of extra water could have enhanced its strength. Generally, the differences between the results are small and it could be concluded that OPCMatrix mixes with OPC, GPC and natural sand demonstrated almost equivalent values.

On the other hand the reaction of GPCMatrix in the incorporation of FRCA appears to be clearly dependent on the type of aggregate. The effects of GPC and OPC-FRCA on compressive strength were opposite, with the first leading to improvement and the latter to remarkable decline. For 25% and 50% replacement accordingly, OPC-FRCA leads to 65% and 70% lower values compared to those obtained with GPC-FRCA.

According to literature a gradual decrease of strength with increasing replacement percentage should have been expected. For low replacement levels several studies report minor effects on OPC mortars' strength and claim the potential of high strength concrete production with appropriate mix design. Apart from this, there are cases when RCA was reported to have had a favourable effect on mixes leading to strength gain (Shi, et al., 2012; Silva, et al., 2014a). The strength enhancement on these cases was correlated to the higher strength of the original material from which the aggregates derived compared to that of the produced concrete (Silva, et al., 2014a). Given the high values demonstrated by the original binders on the present study, this could provide an interpretation of the obtained results. Another possibility is that the w/c ration of the mixes was somehow alternated. This could have occurred either because FRCA absorbed water during mixing or because the hardened mortar deriving from the finely crushed FRCA acted as filler, leading to increase of the overall amount of cementitious materials in the mixes. These two possibilities could have resulted to w/c reduction and consequently to strength enhancement. For high replacement percentages this enhancement could have been counterbalanced by the dryness of the mixes resulting to the observed relative decrease.

This assumption is likely to be true for the OPC-FRCA which demonstrated the tendency to react further with water. This argument could explain the data for OPC_50% OPC mix, which demonstrates strength slightly higher to that of the reference but significantly lower density. Furthermore the thixotropic behaviour of OPCMatrix_GPC indicates a chemical reaction of the FRCA.

For GPCMatrix mixes the effect of OPC-FRCA was detrimental. It was observed that OPC-FRCA addition led to downgrading of GPC mortar regardless the replacement level. Similar effects have been observed in studies investigating the use of geopolymeric matrices for OPC recycling, and the negative effect is attributed to the fact that RCA could not make a positive effect in the chemical reaction process determining the strength of GPC (Shi, et al., 2015; Shi, et al., 2012; Zhang, 2012). On the contrary the addition of GPC-FRCA appears to positively influence the strength development of GPCMatrix, resulting to remarkable increases regardless the aggregate percentage. An interpretation of that effect could be based on the fact that GPC-FRCA derived from a binder with strength and alkalinity higher than that of the final mix. The stronger aggregates could have enhanced the mortar strength similarly to OPCMatrix mixes while it is possible that the alkalis deriving from the original binder led to an increase of the overall alkalinity of the mix. These could lead to higher strength compared to the reference.

It appears that the correlation of mixes' and aggregates' densities to the strength of the resulting mixes is overshadowed by the chemical interaction between the matrices and FRCA.

Based on the above remarks, it seems more likely that the explanation of the results lies in the internal structure of the mortars and the products of the hardening reactions. There is a consensus that the addition of RCA influences the formation of the Interfacial Transition Zone (ITZ) and the products of the hardening reactions of OPC and GPC mixes. The adhered hardened mortar on the aggregates has a significant effect and as it can be inferred from the results and this is quite distinct for FRCA deriving from different matrices. Due to the fact that the binding phases comprising GPC and OPC mortars are quite distinct it is hard to explain the obtained results without microscopic and chemical analysis to support any assumptions.

5.2.5 Flexural Strength

The values obtained from the flexural strength test at 28 days are presented in Table 20.

Table 20 Flexural strength values at 28 days

Flexural strength at 28days (MPa)					
Specimen No	**OPC_100%NA-REF**	**OPC_25%OPC**	**OPC_25%GPC**	**OPC_50%OPC**	**OPC_50%GPC**
1	7,84	8,14	5,63	6,29	6,48
2	7,52	6,74	6,86	6,74	5,73
3	8,14	8,62	7,54	5,78	6,12
Mean value	7,83	7,83	6,68	6,27	6,11
Standard Deviation	0,25	0,80	0,79	0,39	0,31
Specimen No	**GPC_100%NA-REF**	**GPC_25%OPC**	**GPC_25%GPC**	**GPC_50%OPC**	**GPC_50%GPC**
1	6,23	2,76	6,89	3,06	4,75
2	6,92	3,10	6,77	2,84	5,16
3	6,13	3,67	6,01	2,48	4,05
Mean value	6,43	3,18	6,56	2,79	4,65
Standard Deviation	0,35	0,38	0,39	0,24	0,46

The results for the mean flexural strength of the mixes in relation to the FRCA replacement levels are presented in Figure 9.

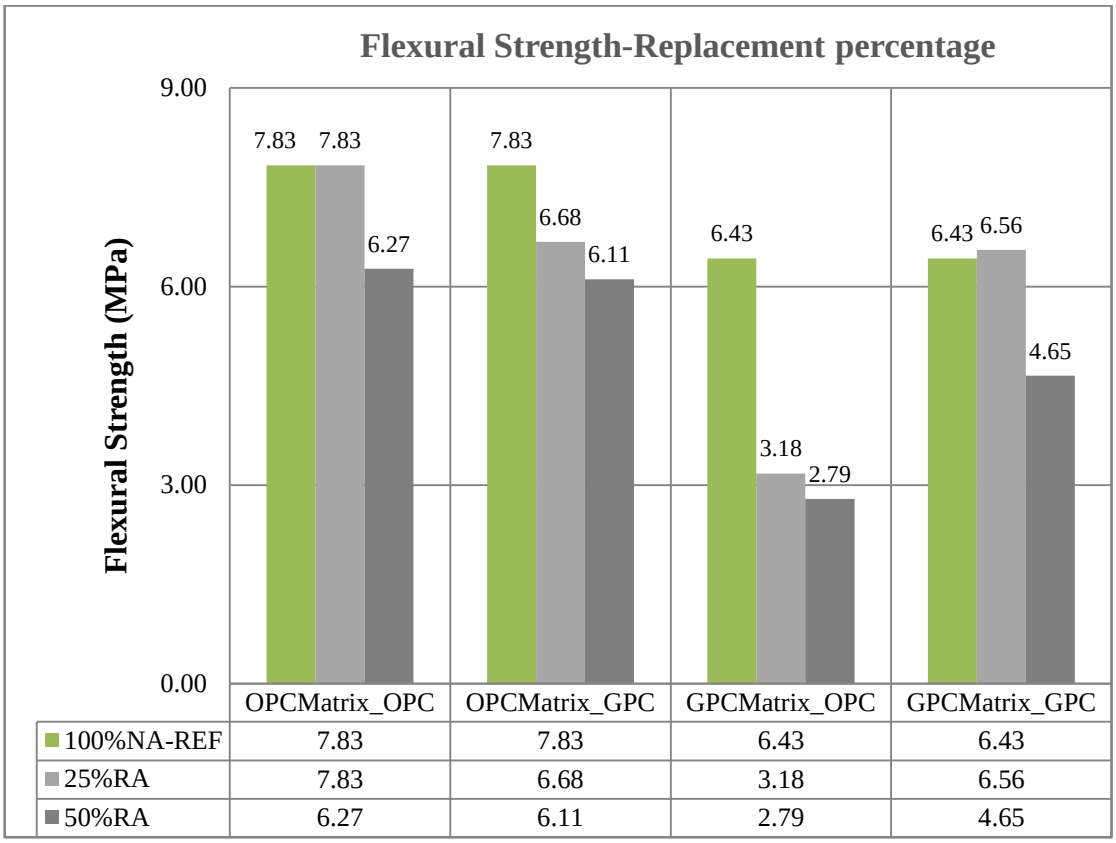


Figure 9 Mean Flexural strength results for all mixes in relation to replacement percentage of FRCA

It is observed that flexural strength presents a reduction with high replacement levels for OPCMatrix and GPCMatrix_GPC mixes, while for low replacement levels the obtained values are almost equal to those of the reference mix. Despite the drop observed with 50% replacement level, the general effect in not detrimental as the reductions are within the range of 20% to 28%. However, the behaviour of GPCMatrix_OPC mix is completely different as it appears that the influence of the aggregate does not depend much on the replacement percentage. Specifically, for 25% OPC-FRCA the flexural strength is 50% lower than that of the reference, while for double replacement level the corresponding reduction is 57%. Generally, GPCMatrix_OPC was the most severely affected combination.

In Figure 10 the results for the mean flexural strength of the mixes in relation to the type of FRCA are presented.

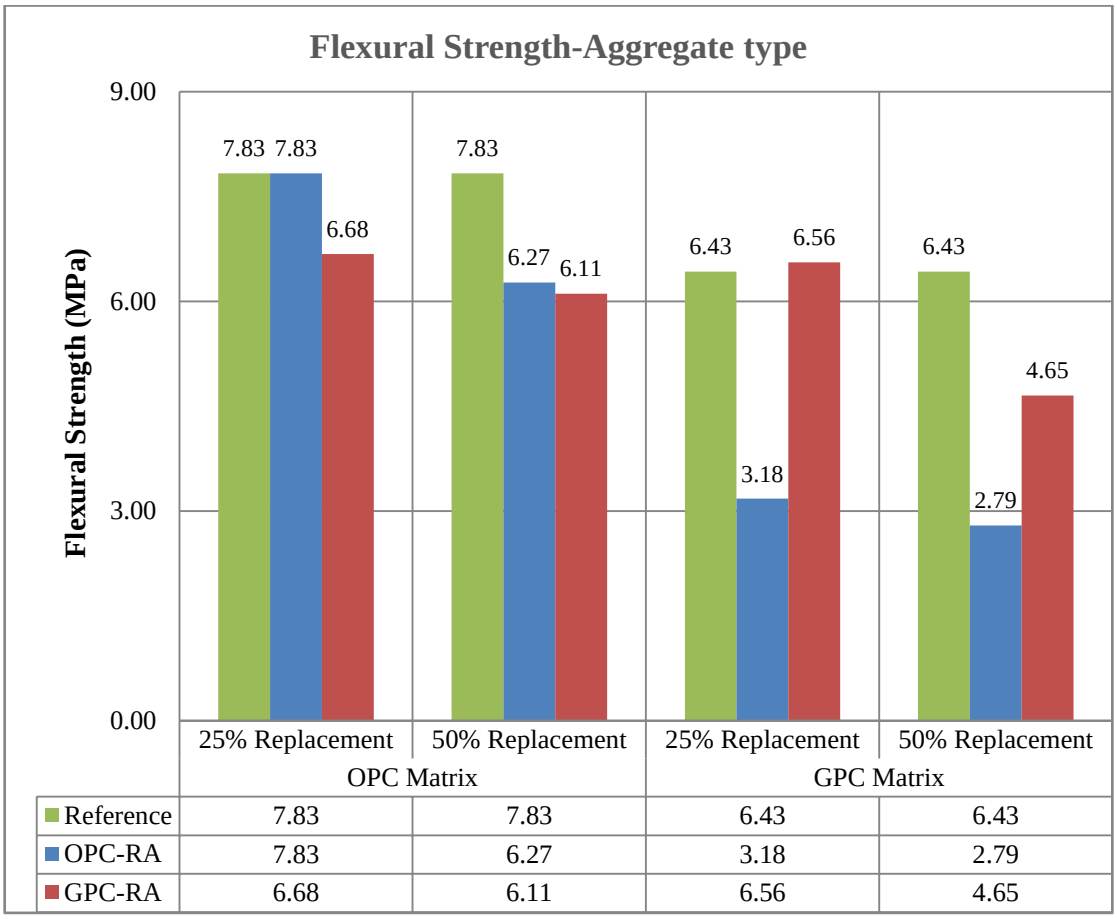


Figure 10 Mean Flexural strength results for all mixes in relation with type of FRCA

For OPCMatrix mixes it appears that GPC-FRCA had a slightly more detrimental effect compared to OPC-FRCA. With 25% replacement it led to 15% reduction of flexural strength while the corresponding value for GPC-FRCA was equal to that of the reference mix. For 50% replacement the difference of flexural strengths obtained with the use of GPC and OPC FRCA was minor (3%). Despite the similar values, the behaviour of the mixes is quite different depending on the type of FRCA. Specifically, the drop in strength for OPCMatrix_GPC occurred with low replacement percentage and did not further increase as percentage doubled. On the other hand for the OPCMatrix_OPC a drop occurred only for high replacement percentage and could be partially due to the water addition.

For the GPCMatrix specimens though the aggregates appear to have had a clear effect, as the use of OPC-FRCA led to 50% lower values compared to GPC-FRCA, regardless the replacement levels. Moreover GPC-FRCA did not appear to have the same enhancing influence on flexural strength as it did on compressive strength.

An observation made during flexural strength testing is that OPCMatrix mortars presented brittle type of failure, while GPCMatrix specimens were suppler.

The trend followed by the OPCMatrix mixes is similar to that identified in the study of Zhao (Table 21) for same size specimens (Zhao, et al., 2015). The results of both studies present similarities as far as the downward trend with increasing replacement levels and the negligible influence of low FRCA levels are concerned.

Table 21 Flexural strength in relation with replacement percentage for mortars with saturated FRCA *Data source*: (Zhao, et al., 2015)

Flexural Strength		
Replacement percentage	**W/C= 0.5**	**W/C=0.6**
0%	12.14	10.63
10%	13.06	10.55
20%	12.05	10.21
30%	10.86	10.00
50%	10.53	9.16
100%	8.54	8.00

As far as GPCMatrix specimens are concerned the mechanisms affecting flexural strength have not been intensively investigated therefore it is hard make any assumptions for the effect of FRCA other than those analysed in the "Compressive Strength" section. Additionally it appears that in GPC mortars the relationship between compressive and flexural strength is different to that of OPC mortars.

Conclusively, it is observed that the effect of FRCA on flexural strength depends more on the type of aggregate although it generally presented a downward trend for higher replacement levels. No distinct correlation between flexural strength and density of mortars or aggregate properties was identified. It is possible that the flexural strength is affected by the same mechanisms as the compressive strength. Despite any theoretical assumptions, adequate information to interpret the results should be obtained by microscopic investigation of the matrix structure and compounds.

5.2.6 Water Absorption

The values obtained from the water absorption test at 28 days are presented in Table 22.

Table 22 Water absorption values at 28 days

Water absorption at 28days					
Specimen No	**OPC_100%NA-REF**	**OPC_25%OPC**	**OPC_25%GPC**	**OPC_50%OPC**	**OPC_50%GPC**
1	4,85%	7,14%	6,72%	11,76%	10,39%
2	4,65%	7,04%	6,63%	12,56%	10,15%
3	5,07%	6,97%	6,64%	11,91%	9,82%
Mean value	4,86%	7,05%	6,66%	12,08%	10,12%
Standard Deviation	0,17	0,07	0,04	0,34	0,23
Specimen No	**GPC_100%NA-REF**	**GPC_25%OPC**	**GPC_25%GPC**	**GPC_50%OPC**	**GPC_50%GPC-**
1	6,34%	10,96%	10,00%	21,00%	10,36%
2	6,67%	11,16%	10,84%	20,68%	10,56%
3	7,37%	10,22%	8,63%	18,59%	10,76%
Mean value	6,79%	10,78%	9,82%	19,06%	10,56%
Standard Deviation	0,43	0,41	0,91	2,01	0,16

The results for the mean water absorption of the mixes at 28days in relation to the RCA replacement levels are presented in Figure 11.

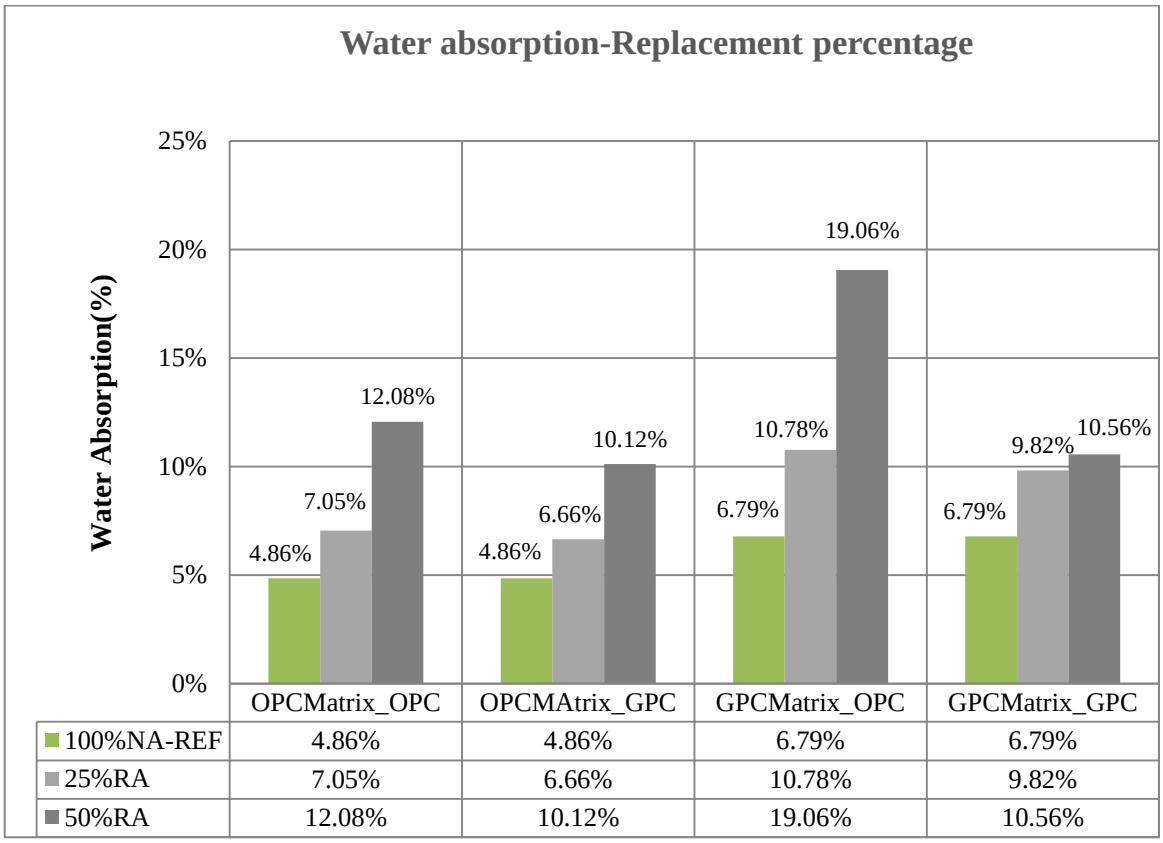


Figure 11 Mean water absorption results for all mixes in relation to replacement percentage of FRCA

This appears that the WA of the mixes is highly depended on the FRCA level, since for all specimens WA presented gradual increase with increasing replacement percentage.

The OPCMatrix_OPC mix presented a 31% increase with 25% replacement while the corresponding value for 50% percentage is 60% higher than that of the reference. The effect of GPC-FRCA on OPCMatrix mixes is similar with 27% increase for low replacement level and 52% for high. It is apparent that WA in OPC mixes exhibited a parallel development as the FRCA percentage increased, with GPC-FRCA resulting to slightly lower values.

For the GPCMatrix_OPC the trend was similar. Low percentage of FRCA resulted to an increase of 37% while for high replacement level the obtained value was 64% higher than that of the reference. The influence of GPC-FRCA on GPCMatrix mixes appeared to be

less depended on replacement levels compared to the other combinations. For addition of 25% FRCA the WA of the mix raised by 30% while for 50% no significant further increase occurs as the obtained value was 35% higher than the reference.

In Figure 12 the results for the mean water absorption of the mixes at 28 days in relation to the type of FRCA are presented.

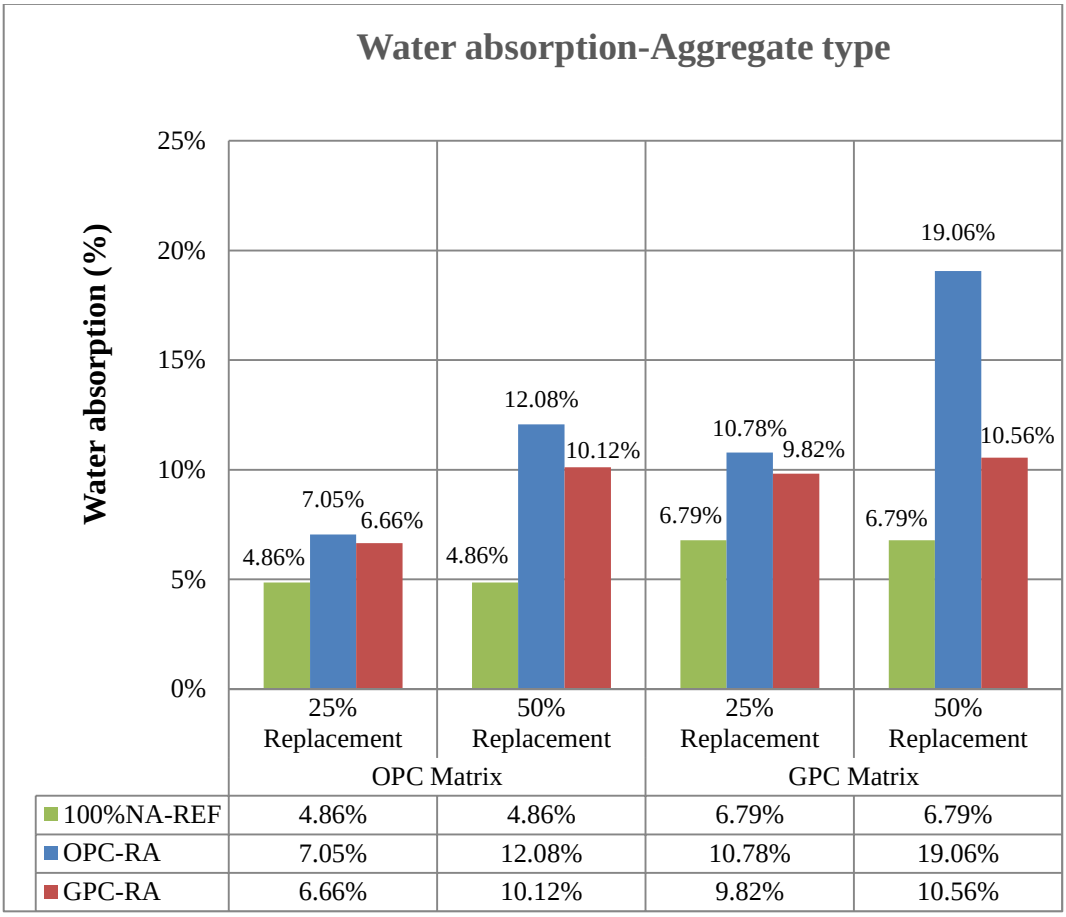


Figure 12 Water absorption results for all mixes in relation with type of FRCA

It appears that generally OPC-FRCA has a slightly more intense effect on WA leading to higher values regardless the replacement percentage.

For the OPC matrices the effect of the two FRCA for low replacement levels is considered equivalent given that the obtained values present a difference of 0.4%. As far as 50% replacement is concerned, although the addition of extra water to OPC_50%OPC mix has probably led to a more cohesive matrix, the mix still demonstrates marginally higher value. Therefore it could be inferred that OPC FRCA has a slightly more detrimental effect on water absorption compared to GPC FRCA.

For the GPCMatrix, the difference between the effects of the two type of aggregate is more prominent. Similarly to the other properties OPC-FRCA resulted in significant downgrading of the GPC mortar. For low replacement percentage the difference of the obtained values is less than 1%, but for 50% percentage the GPC_50%OPC exhibits almost double WA compared to GPC_50%GPC. This could be expected considering the significantly lower density of GPC_50%OPC indicating highly porous structure.

It could be concluded that for OPCMatrix mixes the effect of both types of aggregates is similar and mainly dependent on the replacement level. For the GPCMatrix specimens the influence of OPC-FRCA is apparently more detrimental and becomes much more intense with increasing replacement levels. On the other hand the incorporation of GPC-FRCA appears to affect the mixes only to certain extend regardless the level of replacement. The WA of the aggregates appears to have an influence on the results as in most cases OPC FRCA, had a more severe impact even marginally. In Figure 13 and Figure 14 graphs presenting the correlation between density and WA of the mixes are presented. It is apparent that these two properties are connected by an inverse relationship. As it was expected according to literature findings, with increasing replacement percentage the density of mortar decreases, while the WA increases. Density is an indicator of mortar's porosity; therefore lower density values indicate a more porous structure which leads to higher water absorption.

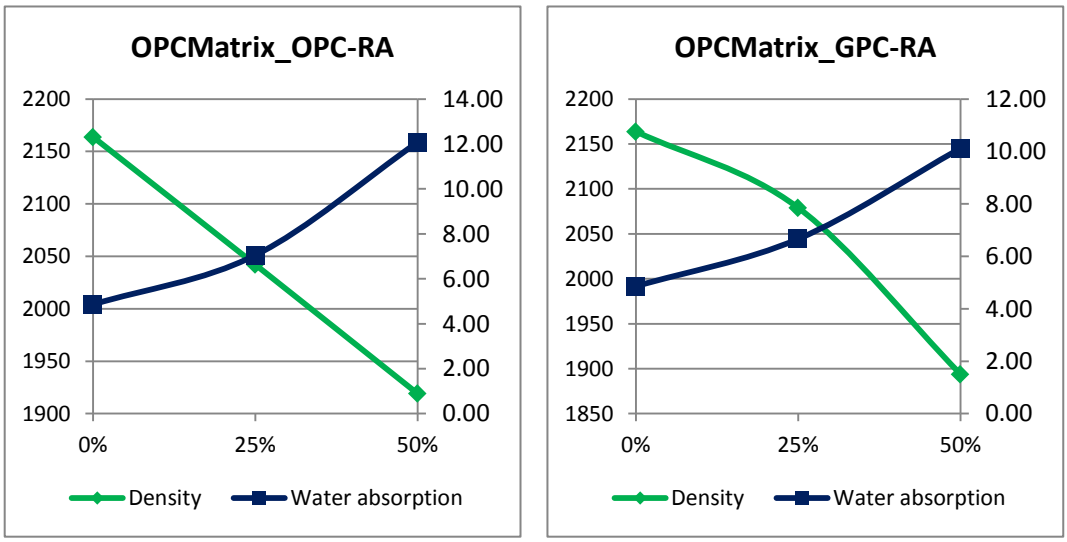


Figure 13 Correlation of density and water absorption with replacement percentage for OPCMatrix specimens

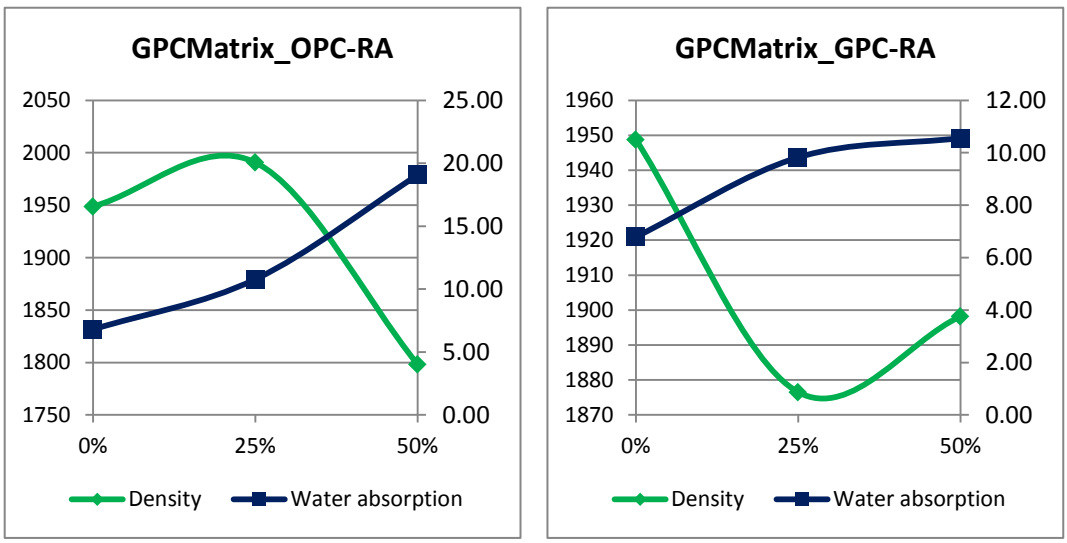


Figure 14 Correlation of density and water absorption with replacement percentage for GPCMatrix specimens

The obtained results are in accordance with the literature findings and the aggregate WA values. The upwards trend of WA with increasing FRCA levels was expected due to the more porous structure of FRCA compared to FNA, attributed the hardened mortar. This leads to an overall increase in the open pores in the concrete matrix. With increasing amount of FRCA in the mortar the porosity of the mixes increases leading to higher WA. This is confirmed by the above figures.

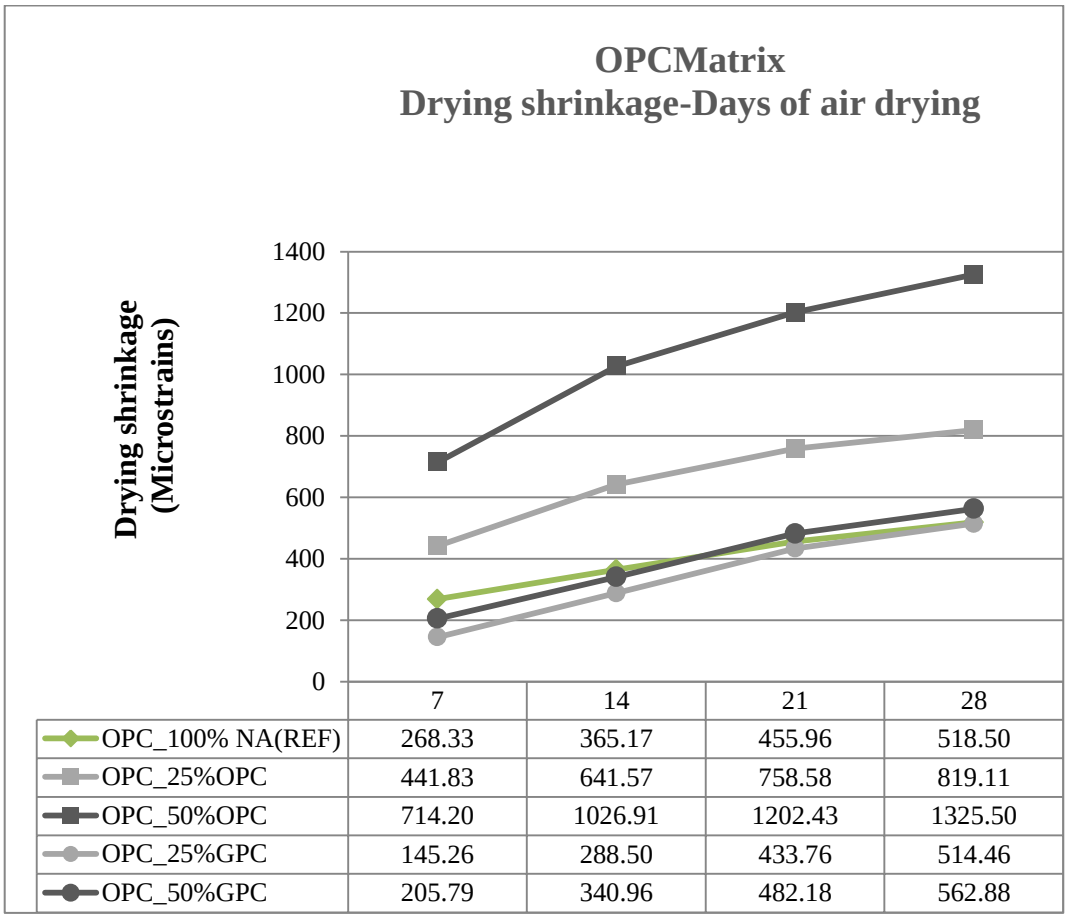
An explanation of the WA mechanism in RAC is given by Wai "*The increase in WA is due to the high absorption capacity of the RCA itself, which creates higher osmosis pressure within the concrete. When the dry specimens are immersed into the water during testing, the specimens with high osmosis pressure tend to absorb more water from the surrounding*

of the specimens. In addition, the RCA is a porous material. It corresponded to high permeability properties for the concrete and higher chances of interconnection within the micro structure system of the specimen." (Wai , et al., 2012) , p. 570. This probably applies to both OPC and GPCMatrix specimens. Although no sufficient information is available to explain in depth the behaviour of GPCMatrix mortars it could be assumed that OPC and GPC FRCA have an influence on WA similar to that on the other properties. Specifically, OPC-FRCA apparently leads in a downgrading of the matrix which becomes more intense as the replacement increases. Although GPC-FRCA appeared to affect the GPCMatrix this is does not go further a certain limit regardless the aggregate percentage. It is possible that the increase of porosity caused by GPC-FRCA is at some point counterbalanced by the enhancing effect of higher alkalinity on the on the matrix structure.

According to the above observations, although the results could be partially explained by correlating the mechanical properties of mortars and aggregates an in-depth interpretation of the result requires the examination of the mortars' microstructure and the reaction products.

5.2.7 Drying Shrinkage

In Figure 15 the results for the drying shrinkage of the OPCMatrix mixes in relation to RCA replacement levels and days of air drying are presented.



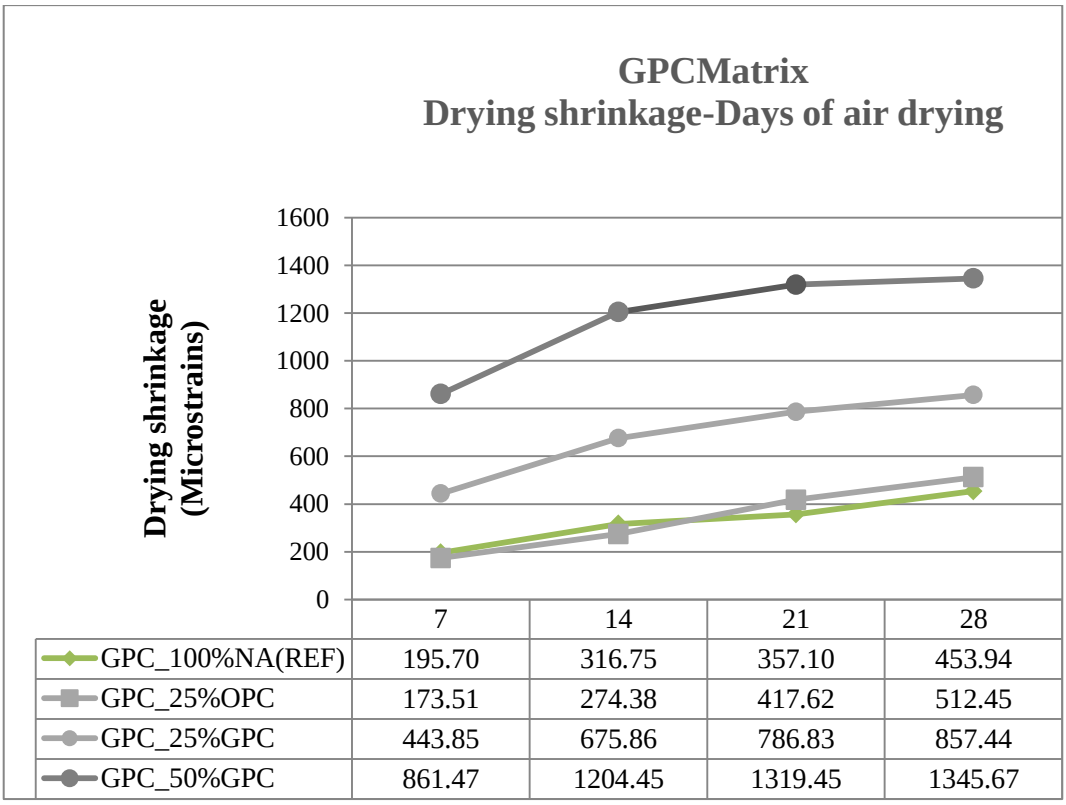
	7	14	21	28
OPC_100% NA(REF)	268.33	365.17	455.96	518.50
OPC_25%OPC	441.83	641.57	758.58	819.11
OPC_50%OPC	714.20	1026.91	1202.43	1325.50
OPC_25%GPC	145.26	288.50	433.76	514.46
OPC_50%GPC	205.79	340.96	482.18	562.88

Figure 15 Development of mean drying shrinkage during 28day air drying period for OPCMatrix mixes

The OPC-FRCA appeared to have a remarkably severe effect on shrinkage. It is observed that OPCMatrix_OPC mixes presented significantly higher values compared to the others during the whole air drying period. Specifically, OPC_50% OPC presented shrinkage approximately 60% higher than that of the reference throughout the whole duration of the test, while for OPC_25%OPC the corresponding increase was 30 %. The effect of GPC-FRCA is somehow different. The OPCMatrix_GPC mixes presented lower shrinkage than the reference at the beginning of the air drying period and resulted to almost equal values after 28 days. Indicatively, at 7 days of air drying the shrinkage of OPC_25%GPC and OPC_50%GPC has 45% and 23% lower compared to reference.

A noteworthy observation is that the rate of shrinkage in mixes with OPC, GPC and natural sand appears to be different. For OPCMatrix_OPC most of the shrinkage occurs at the first 7 days, while for the other mixes the length reduction occurs gradually.

Figure 16 presents the results for the drying shrinkage of the GPCMatrix mixes in relation with to RCA replacement levels and days of air drying. No data is presented for the GPC_50%OPC mix due to damaging of the specimens.



	7	14	21	28
GPC_100%NA(REF)	195.70	316.75	357.10	453.94
GPC_25%OPC	173.51	274.38	417.62	512.45
GPC_25%GPC	443.85	675.86	786.83	857.44
GPC_50%GPC	861.47	1204.45	1319.45	1345.67

Figure 16 Development of mean drying shrinkage during 28day air drying period for GPCMatrix mixes

The effect of the two aggregate type is opposite on the GPCMatrix mixes, with GPC-FRCA affecting negatively drying shrinkage. For 25% replacement by GPC-FRCA values approximately 50% higher than the reference are obtained for the whole test duration. The increase was up to 77% for 50% replacement. The effect of OPC-FRCA is significantly different since the OPC_25%OPC presented lower shrinkage than the reference (11% at 7 days and 22% at 14 days) before resulting to 15% and finally 11% higher value.

It is observed that GPCMatrix_GPC mixes exhibited the biggest part of their total shrinkage during the first days of air drying. This was expected as according to literature

ambient cured GPC expels most of the water from its matrix within two weeks after casting. On the other hand GPC_25%OPC presented a gradual shrinking trend.

It could be concluded that for both matrix types the type of aggregate is the most influencing parameter, with OPC-FRCA affecting more the OPCMatrix and GPC-FRCA the GPCMatrix. This is also confirmed by Figure 18. For the above mentioned aggregate-matrix combinations, shrinkage appeared to be quasi linearly connected with replacement levels, since double percentages resulted to almost double values. For OPCMatrix the GPC-FRCA had marginal influence regardless the replacement level (Figure 17). Due to lack of data it is not possible to confirm whether the same is true for GPCMatrix and OPC-FRCA.

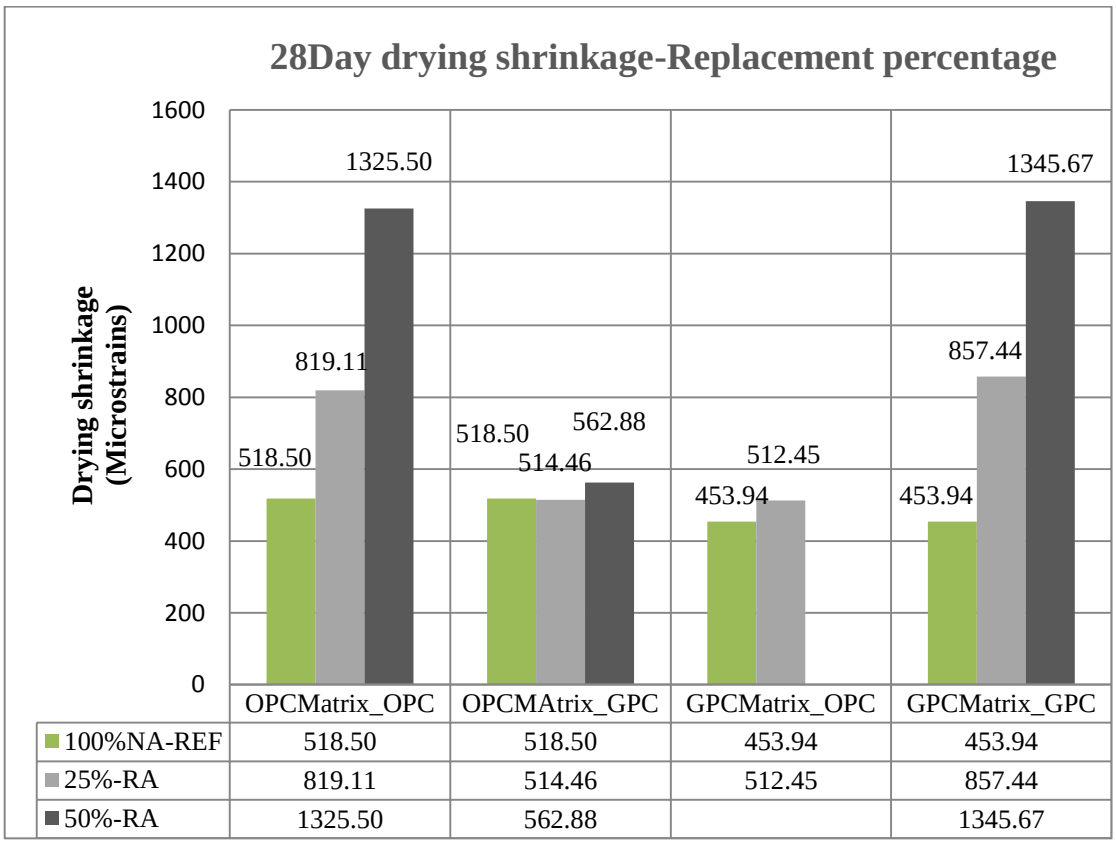
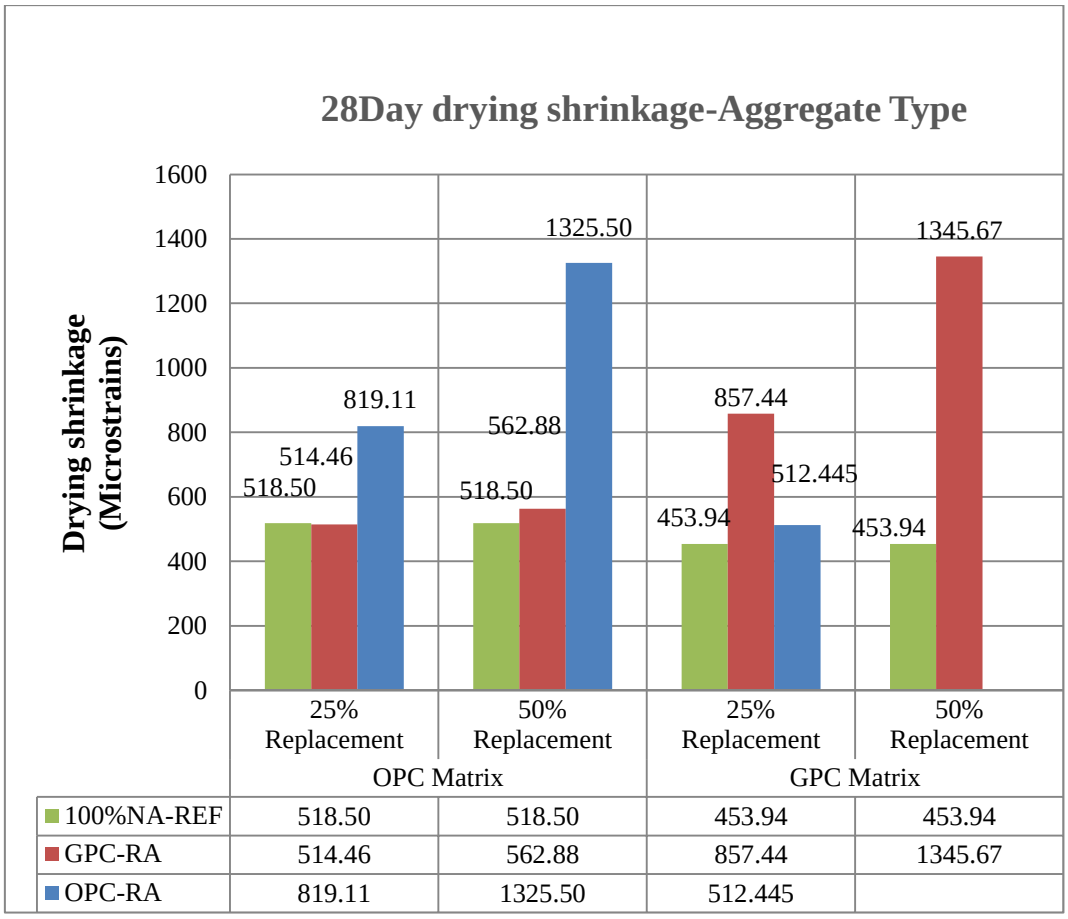


Figure 17 Mean drying shrinkage results after 28 days of air drying in relation to replacement percentage for all mixes



	OPC Matrix		GPC Matrix	
	25% Replacement	50% Replacement	25% Replacement	50% Replacement
100%NA-REF	518.50	518.50	453.94	453.94
GPC-RA	514.46	562.88	857.44	1345.67
OPC-RA	819.11	1325.50	512.445	

Figure 18 Mean drying shrinkage results after 28 days of air drying in relation to type of FRCA for all mixes

The obtained results are in accordance with the literature findings where increases in shrinkage up to 70% are reported (Zega & di Maio , 2011; Hansen, n.d.). Most studies connect drying shrinkage of OPC with cement content on the mix, which in the case of RAC increases proportionately to replacement levels because of the adhered cement paste on the aggregates. This could justify the high increases demonstrated by mixes with OPC-FRCA and the minor effect of replacement by GPC-FRCA. As mentioned before, OPC-FRCA is very likely to have acted as cement binder given it reacted with water. Also GPCs stop shrinking after they expel all the water from their matrix. Given that it is assumed that GPC-FRCA exhibited no further shrinkage in the new mixes.

For the results demonstrated by the GPCMatrix specimens a possible explanation could be that the GPC-FRCA alkalinity probably influenced that of the mix alternating the drying shrinkage mechanism among others.

6 Conclusions & Suggestions for Future Research

The results generally indicated that fly ash/ slag based Geopolymer concrete is possible to be recycled in mortars with both OPC and GPC matrices. Its influence on OPC mortar properties was similar to that of OPC recycled aggregates, while it proved to have an enhancing effect on most of the GPC mortar properties. Additionally, the investigated mechanical and chemical characteristics of the resulting GPC aggregate proved it to be appropriate for use in mortars.

GPC-FRCA demonstrated almost equal density and significantly lower water absorption compared to OPC-FRCA. The main concern about GPC recyclability was the potential alkali-silica-reactivity of the resulting aggregates. Although the original GPC-binder used contained pieces of unreacted material, none of the specimens demonstrated expansion indicating potential reactivity of GPC-FRCA. Only the GPC_25% OPC mix specimens exhibited expansions leading to inconclusive results.

The performance of OPCMatrix mixes incorporating GPC-FRCA was similar or even better than that of the corresponding mixes with OPC-FRC. For GPCMatrix mixes on the other hand although OPC-FRCA had a negative influence, the effect of GPC-FRCA was enhancing in most cases.

Density and workability of all mixes presented a decrease with increasing replacement levels. The effect of OPC-FRCA was more intense on flow for both matrix types resulting to unworkable mixes and porous structures.

No significant variations where observed in compressive strength of OPCMatrix mixes with both types of aggregate. For GPCMatrix specimens the effect of OPC-FRCA was diminishing and not dependent on the replacement level. On the contrary GPC-FRCA resulted on in significant strength improvement, with the result not being substantially influenced by replacement levels.

For flexural strength of OPCMatrix mixes no important variations were obtained with low replacement levels, while slight reductions occurred for high percentages. In GPCMatrix mixes the effect of FRCA was similar to that on compressive strength.

Water absorption of the resulting mixes demonstrated an almost proportionally increasing trend with increasing replacement levels. The effect of both types of aggregate was similar on OPC mixes, with OPC-FRCA leading to slightly higher values. This was related to its higher water absorption. The mixes with GPCMatrix and OPC-FRCA demonstrated the higher water absorption values, with those incorporating GPC-FRCA being the least affected.

GPC-FRCA had no effect on drying shrinkage of OPCMatrix mixes, while OPC-FRCA led to significant increases depending on the replacement level. Contrary to other results GPC-FRCA had a detrimental effect on GPCMatrix mixes drying shrinkage. They led to significantly higher values that presented an upward trend with increasing replacement percentages. Low replacement by OPC-FRCA had a minor effect on shrinkage.

Except for flow and water absorption the influence of the FRCA on the other mortar properties did not appear to depend essentially on aggregates' mechanical characteristics, although the high strength of the original binders is considered to have played a role. The variation of the results indicates that the effect of FRCA on the mortars depended more on their influence on the hardening reactions of the binders and the products of those reactions Therefore, although potential explanations were provided in the discussion, an in depth interpretation of the results and understanding of the macro scale behaviour requires the investigation of the underlying hardening mechanisms of the mortars.

Concerning the inconclusiveness at some parts of the present project, microscopic analysis of the mortars would be suggested. Specifically, the investigation of the development of the interfacial transition zone (ITZ), the identification of the reaction products and the amorphous and crystalline phases for both matrices GPC should by investigated by commonly used methods such as, scanning electron microscopy (SEM), optical microscopy under transmitted light, energy dispersive x-ray spectroscopy (EDX) and x-ray diffraction (XRD).

Also, further investigation on the alkali-silica reactivity of GPC RCA is required given the followed method is an accelerated procedure, used mainly for screening of the aggregates. Additionally, the aggregates used in this study where no reactive considering this, the effect of GPC RA in mixes with siliceous potentially reactive natural aggregates should be investigated. Therefore further testing using either the mortar bar method or the concrete

prism method in various aggregate-matrix combinations and microscopic examination to identify ASR gel would provide sufficient results to conclude about GPC-RCA reactivity.

Finally, due to limitations imposed by time and nature of the present study the investigation of a single combination of OPC and GPC was possible. There is a plethora of parameters affecting OPC and GPC properties, the alternation and interaction of which could lead to results completely different to the obtained ones. Some of these parameters that could be investigated in future researches are: wide range of raw materials and mix design of recycled GPC, mix design and nature of the "hosting matrix", the recyclability of GPC mortars or concretes and the effect of original aggregates' chemical composition, various RCA particle sizes, incorporation of GPC RCA in mortar or concrete mixes with various types of natural aggregates, relationship of strength between original and new mortar, optimisation of mix design of RAC incorporating GPC-RCA.

It is become apparent that the enumeration of these parameters would result in an exhaustive list since the potential of recycling geopolymer cement opens up a completely new field of research. This thesis is the evaluation of only one of the potential ways of recycling fly ash/slag based geopolymer.

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